Chapter 20

The Heart

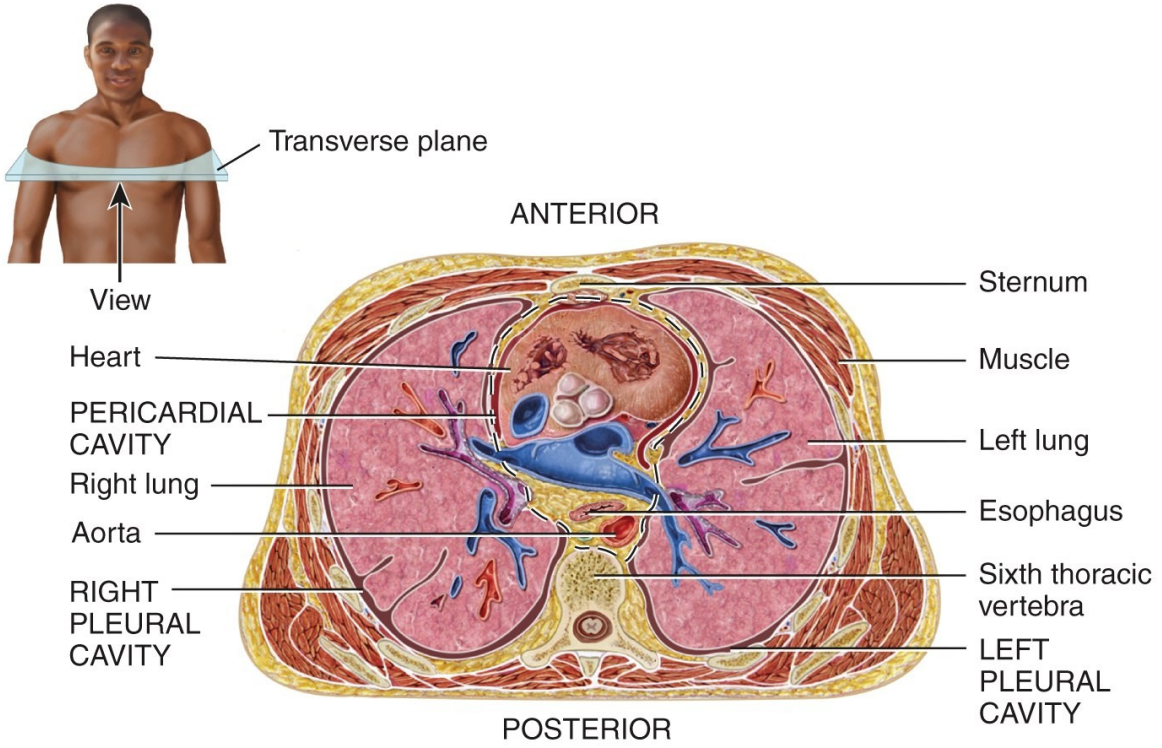
The Circulatory System

- The heart is the pump of the circulatory system.
  - It weighs about 350g (about the size of a closed fist)
  - it beats >10,000 times per day

- The heart and blood vessels transport water, gases (O_2, CO_2, N_2), proteins and hormones throughout the body

Heart Location

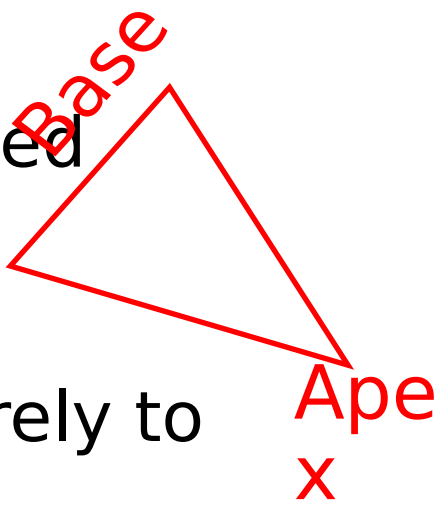
- The heart is located in the mediastinum, which extends from the sternum anteriorly to the vertebral column posteriorly, and lies medially between the tw membranes that cover ther



(a) Inferior view of transverse section of thoracic cavity showing heart in mediastinum

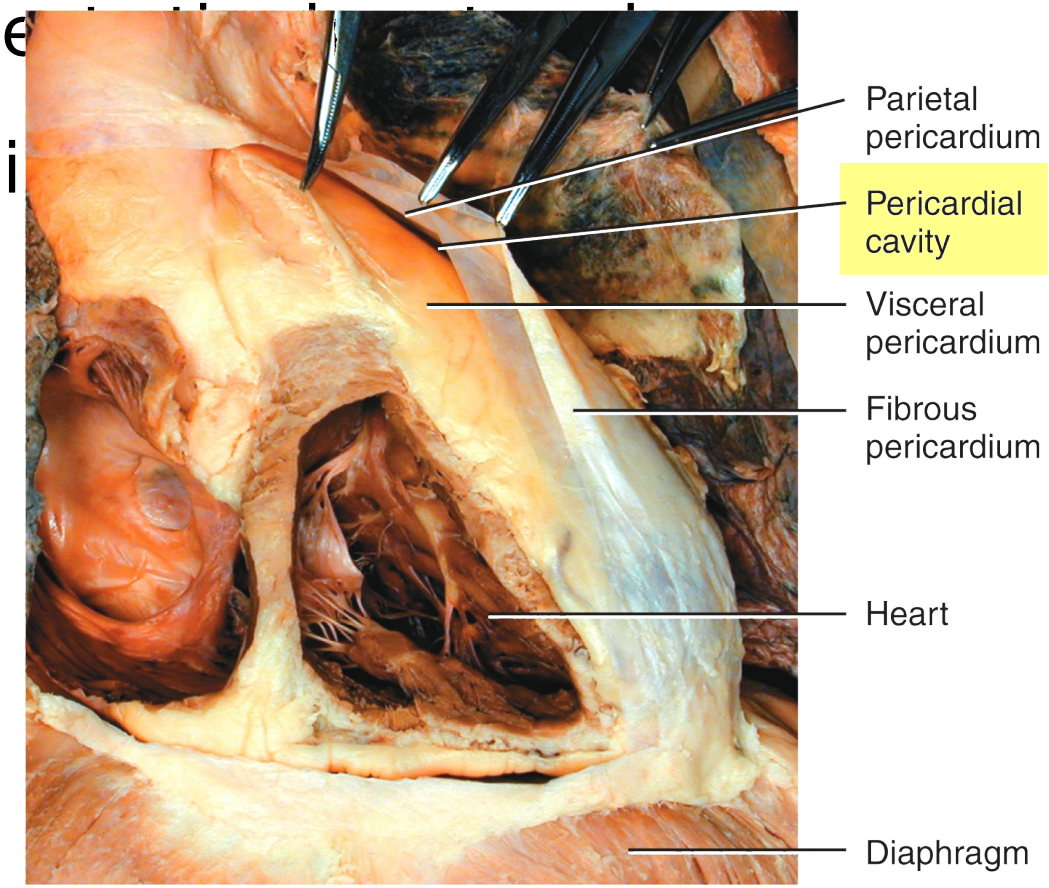
Heart Location

- The mediastinum has anterior, middle, and posterior compartments. The heart is located in the **middle mediastinum.**
- 2/3 of the heart's mass is just barely to the left of the midline.
- The **base** of the heart is tipped up medially and posteriorly, while the **apex** projects inferiorly and laterally.



The Pericardium

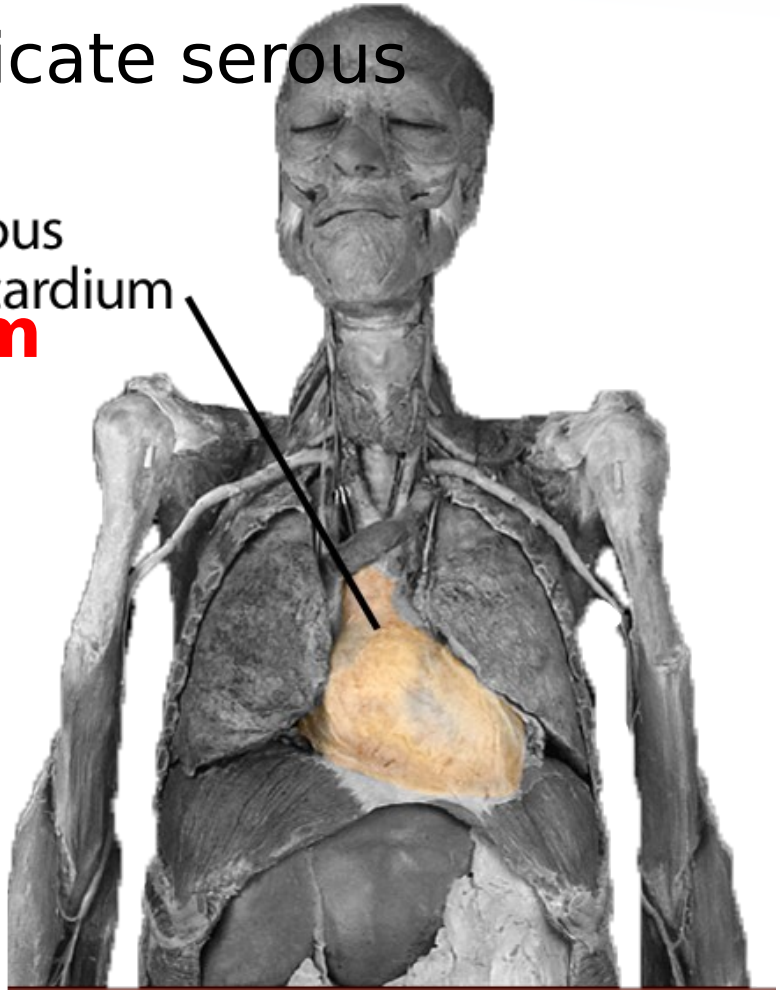
- The **pericardium** is the membrane that surrounds and prote… retains its position i… the mediastinum (while allowing for some freedom of movement).



(f) Layers of the pericardium

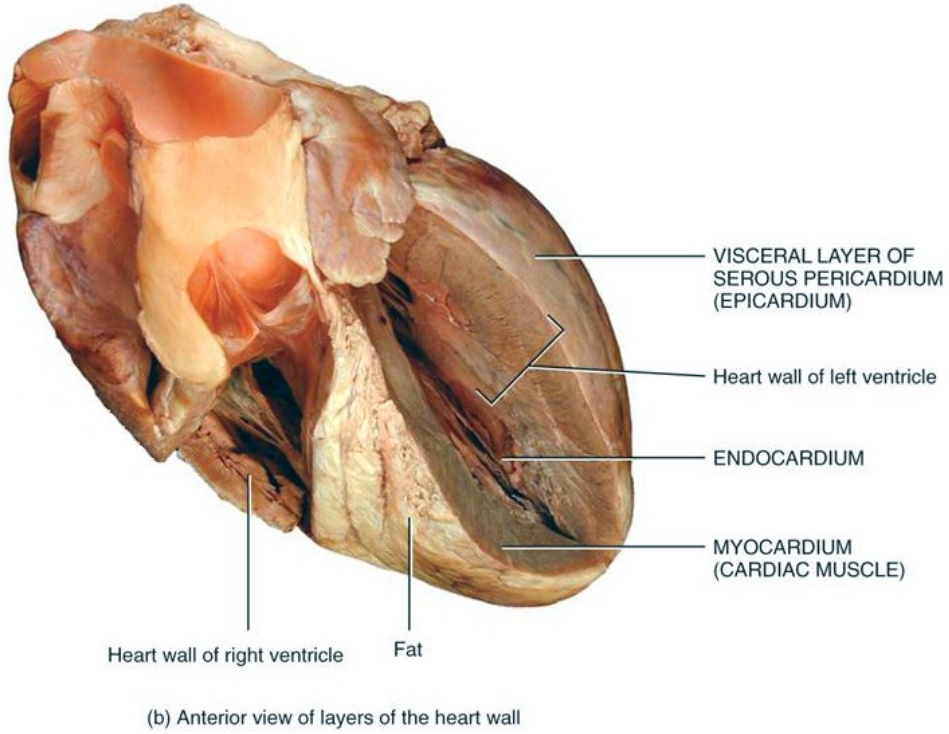
The Pericardium

- The pericardium is composed of a tough outer fibrous layer lined by a delicate serous membrane.
  - The **fibrous pericardium** is a very dense and non-flexible connective tissue that helps protect and anchor the heart.



The Pericardium

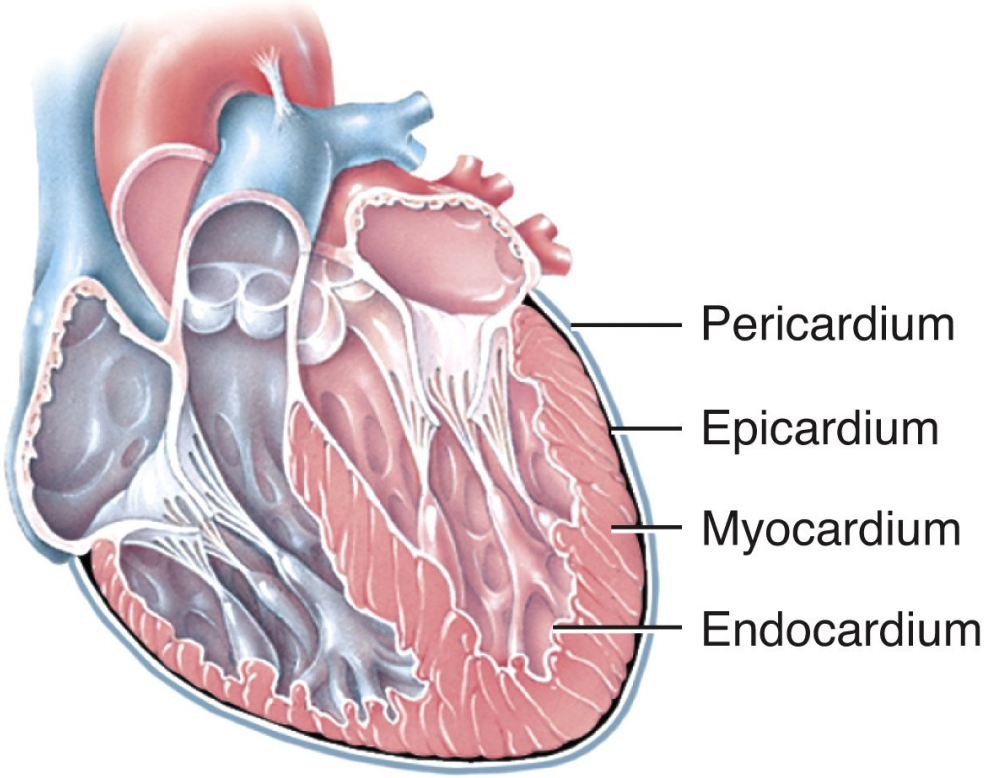
- The inner **serous pericardium** is subdivided into a **parietal layer** which adheres to the outermost fibrous layer and a **visceral layer** which is also viewed heart wall.
- A thin pericardial flui lubricates the space between the viscera and parietal pericardium.



(b) Anterior view of layers of the heart wall

Layers of the Heart Wall

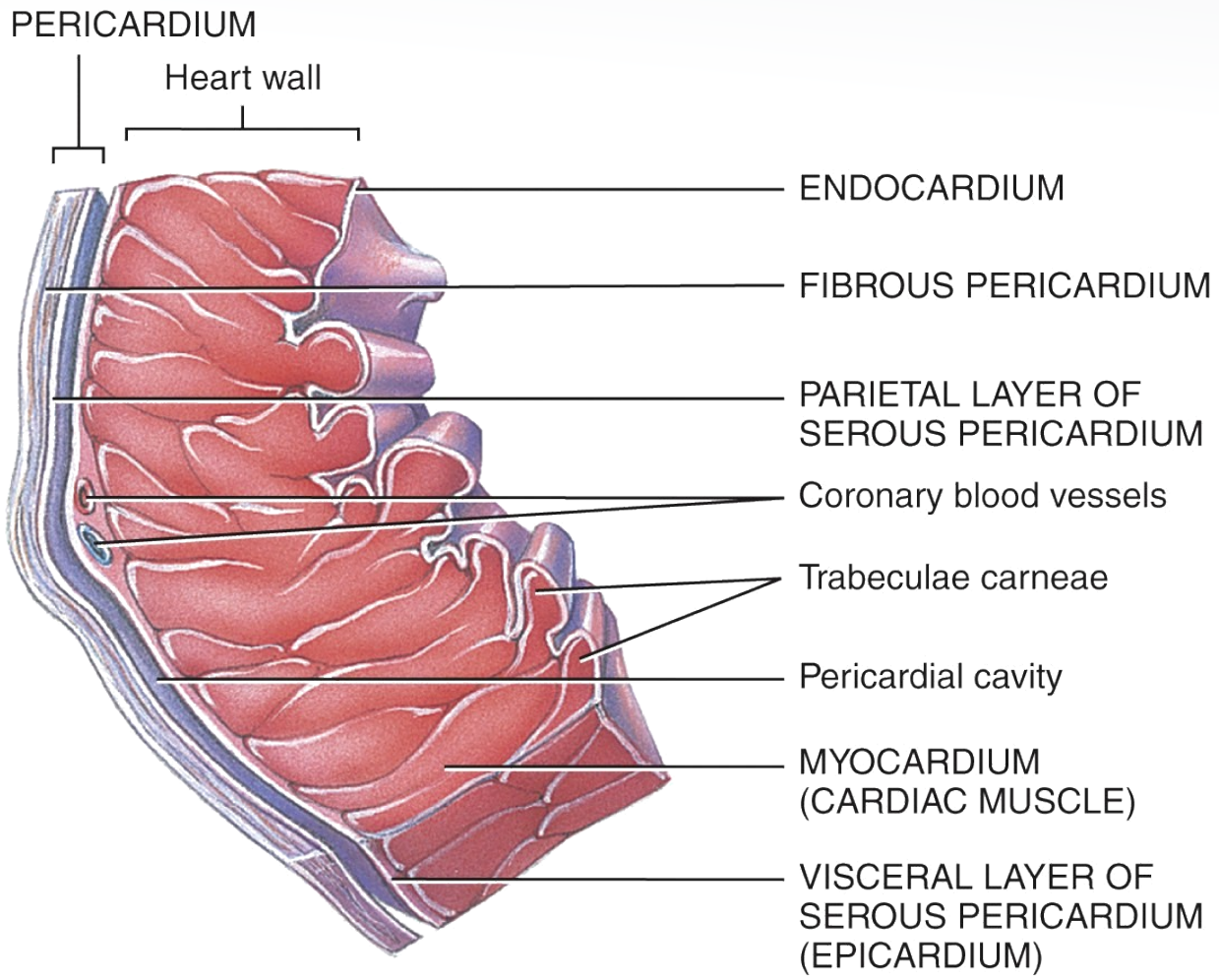
- The wall of the heart is composed of three distinct layers. From superficial to deep they are:
  - The **epicardium**
  - The **myocardium**
  - The **endocardium**



Layers of the Heart Wall

- The **epicardium**, the thin, transparent outer layer of the heart wall, is also called the visceral layer of the serous pericardium.
- The **myocardium**, the thick middle layer, is composed of cardiac muscle.
- The **endocardium** is a simple squamous epithelium (known throughout the circulatory system as "endothelium").

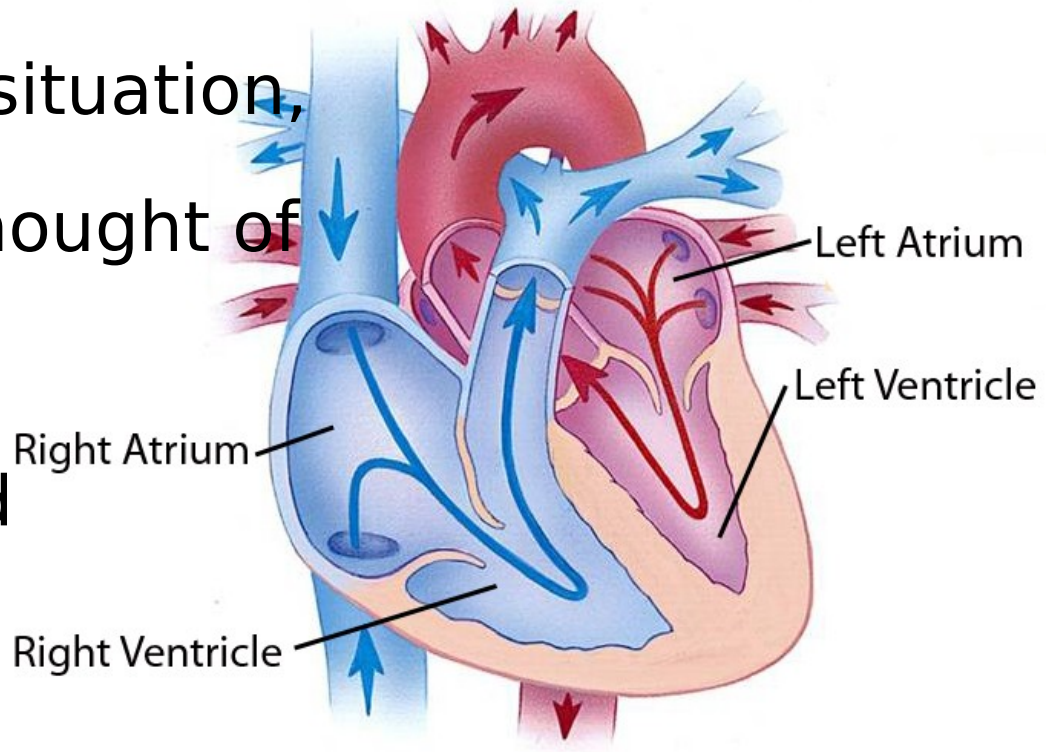
Layers of the Heart Wall



(a) Portion of pericardium and right ventricular heart wall showing divisions of pericardium and layers of heart wall

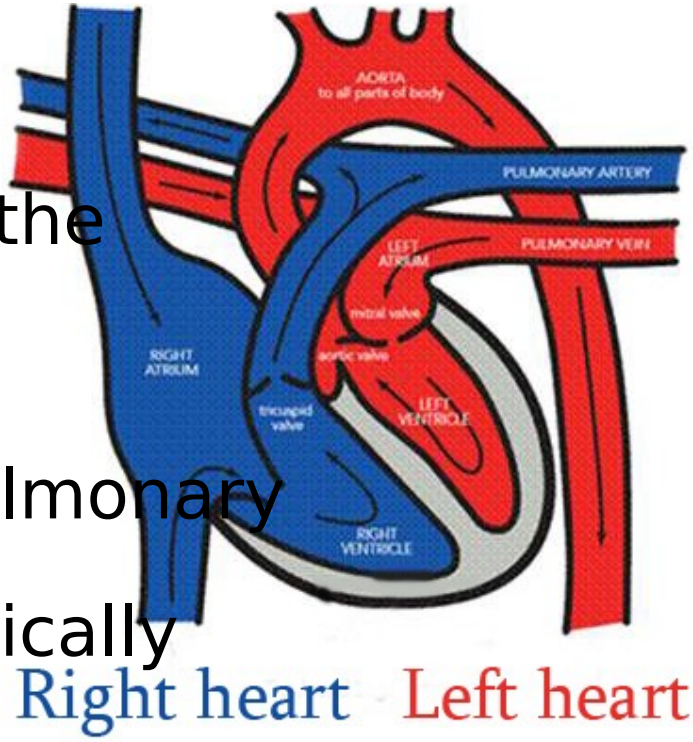
Chambers of the Heart

- The heart has 4 Chambers:
  - The upper 2 are the right and left **atria**.
  - The lower 2 are the right and left **ventricles**.
- Depending on the situation, the heart can be thought of as “right and left” pumps, or “top and bottom” pumps.



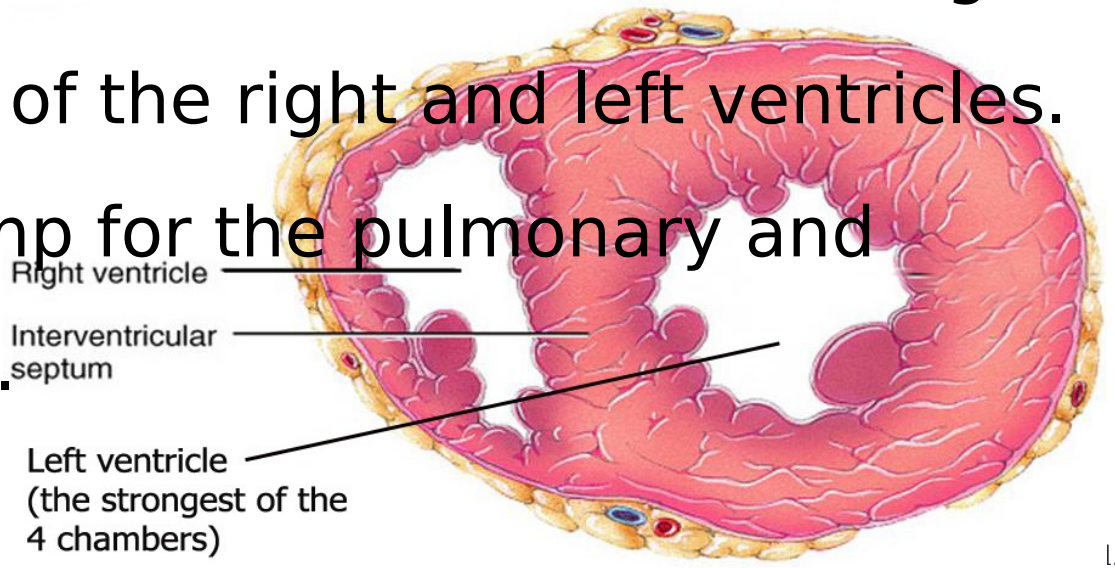
Chambers of the Heart

- The **“right heart”** consists of the right atrium and right ventricle, taking venous blood from the body and pumping it to the lungs for oxygenation.
- The **"left heart"** consists of the left atrium and left ventricle, taking freshly oxygenated pulmonary blood and pumping it systemically (meaning to the body).



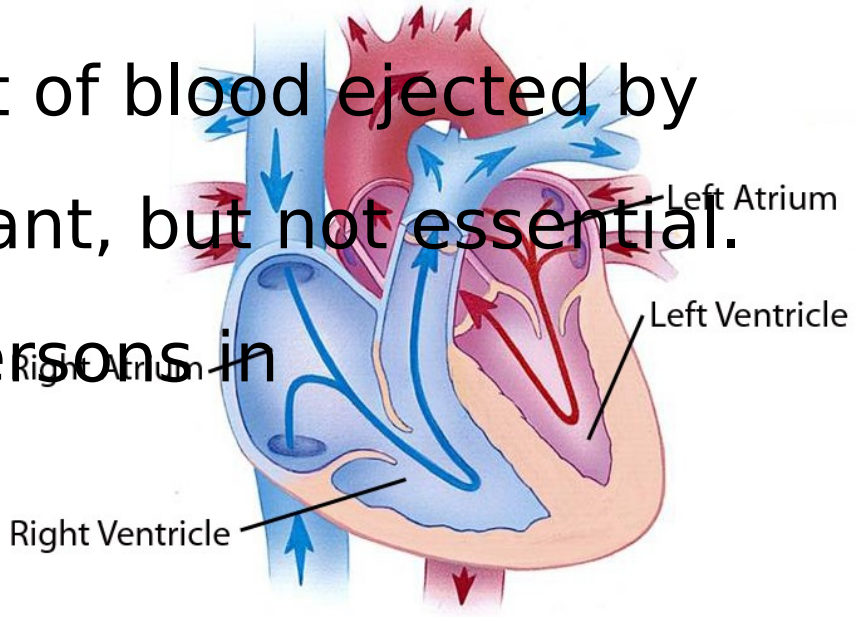
Chambers of the Heart

- The **“top part of the heart”** is a weak pump consisting of the right and left atria. It loads the ventricles by giving an “atrial kick” before the ventricles contract.
- The **"bottom part of the heart"** is a strong pump consisting of the right and left ventricles. It’s the main pump for the pulmonary and systemic circuits.



Chambers of the Heart

- Even without atrial function, blood flows passively down into the ventricles of the bottom heart.
  - The "atrial kick" is responsible for only a 20% increase in the amount of blood ejected by the ventricles - important, but not essential.
- There are many older persons in chronic atrial fibrillation (no atrial kick), that still

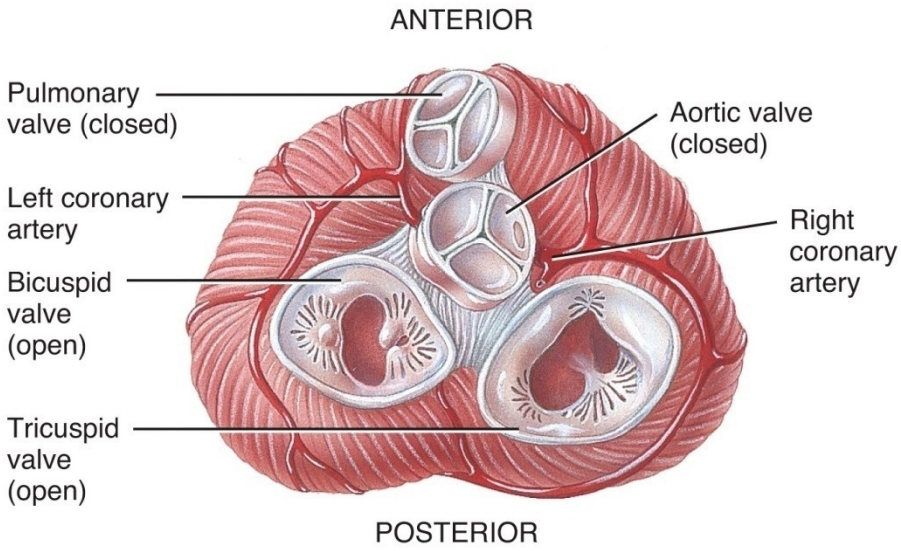


Heart Valves

- Blood always flows from an area of high pressure to an area of low pressure.
- The flow of blood (dictated by differences in pressure, not muscles), operates the valves of the heart.
- Valves operate in pairs:
  - **Atrioventricular valves** open to allow blood to flow from the atria into the ventricles.
  - **Outflow (semilunar) valves** open to allow blood to flow from the ventricles into the

Heart Valves

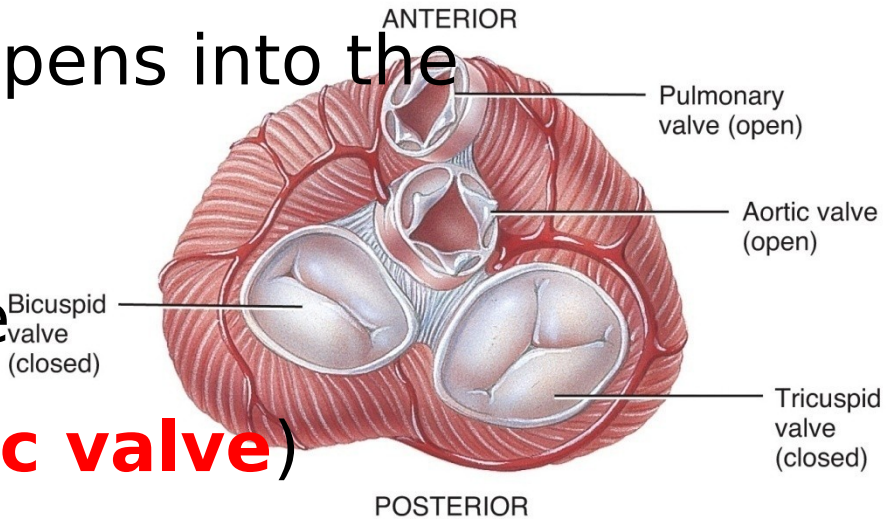
- Atrioventricular **(AV)** valves are positioned at the entrance to the ventricles:
  - The right AV valve (also called the **tricuspid valve** because of its three leaflets or cusps) opens into the right
  - The left AV valve (also called the bicus or **mitral valve**) ope into the right ventric



(d) Superior view with atria removed: pulmonary and aortic valves closed, bicuspid and tricuspid valves open

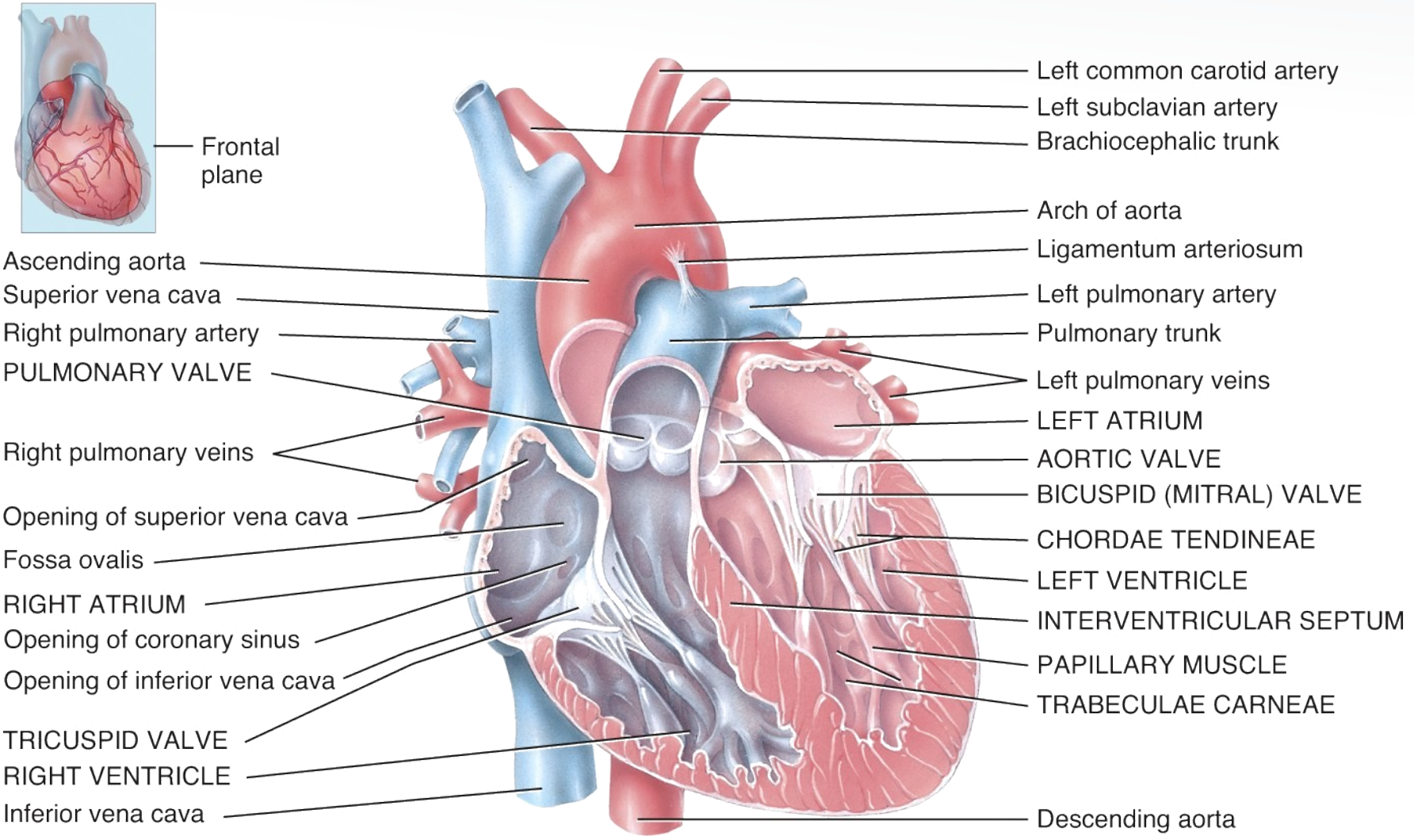
Heart Valves

- The outflow valves are positioned at the entrance to the outflow vessels leading into the pulmonary and systemic circulation:
  - The right outflow valve (also called the **pulmonary valve**) opens into the pulmonary trunk.
  - The left outflow valve (also called the **aortic valve**) opens into the aortic arch.



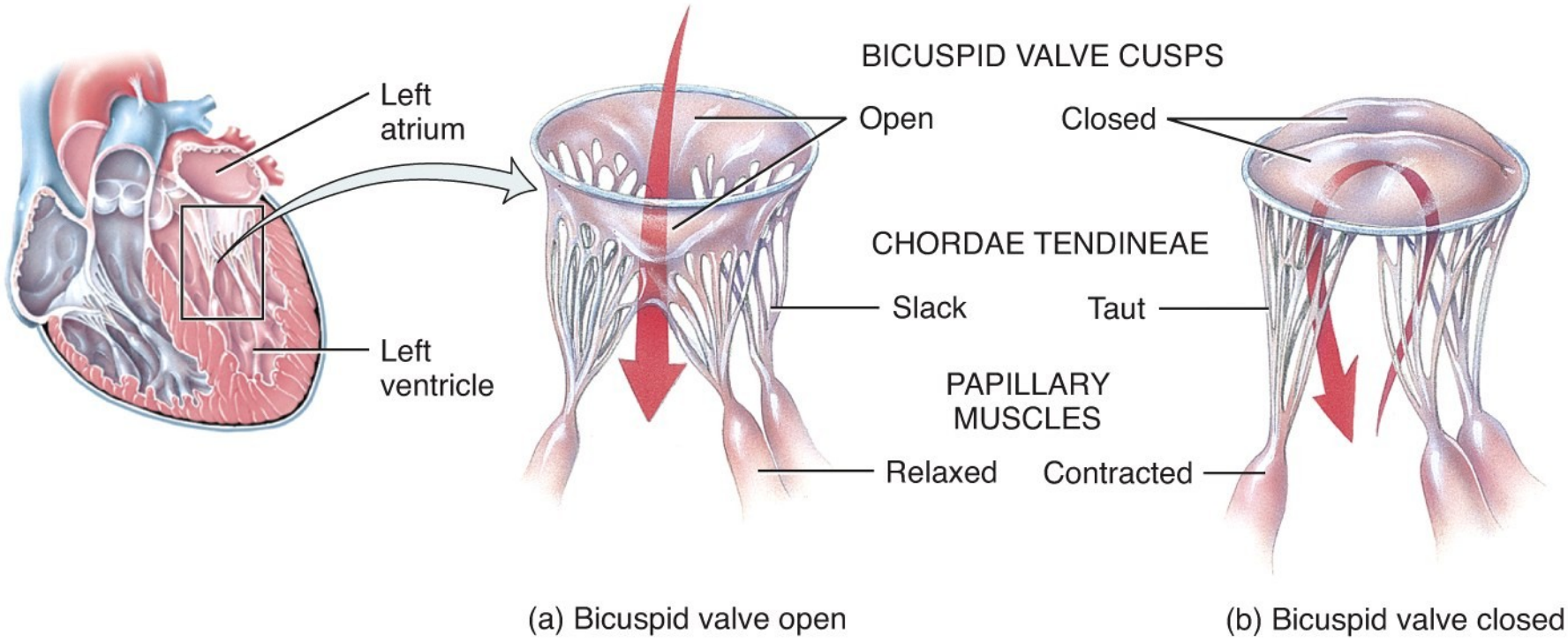
(e) Superior view with atria removed: pulmonary and aortic valves open, bicuspid and tricuspid valves closed

Heart Valves



(a) Anterior view of frontal section showing internal anatomy

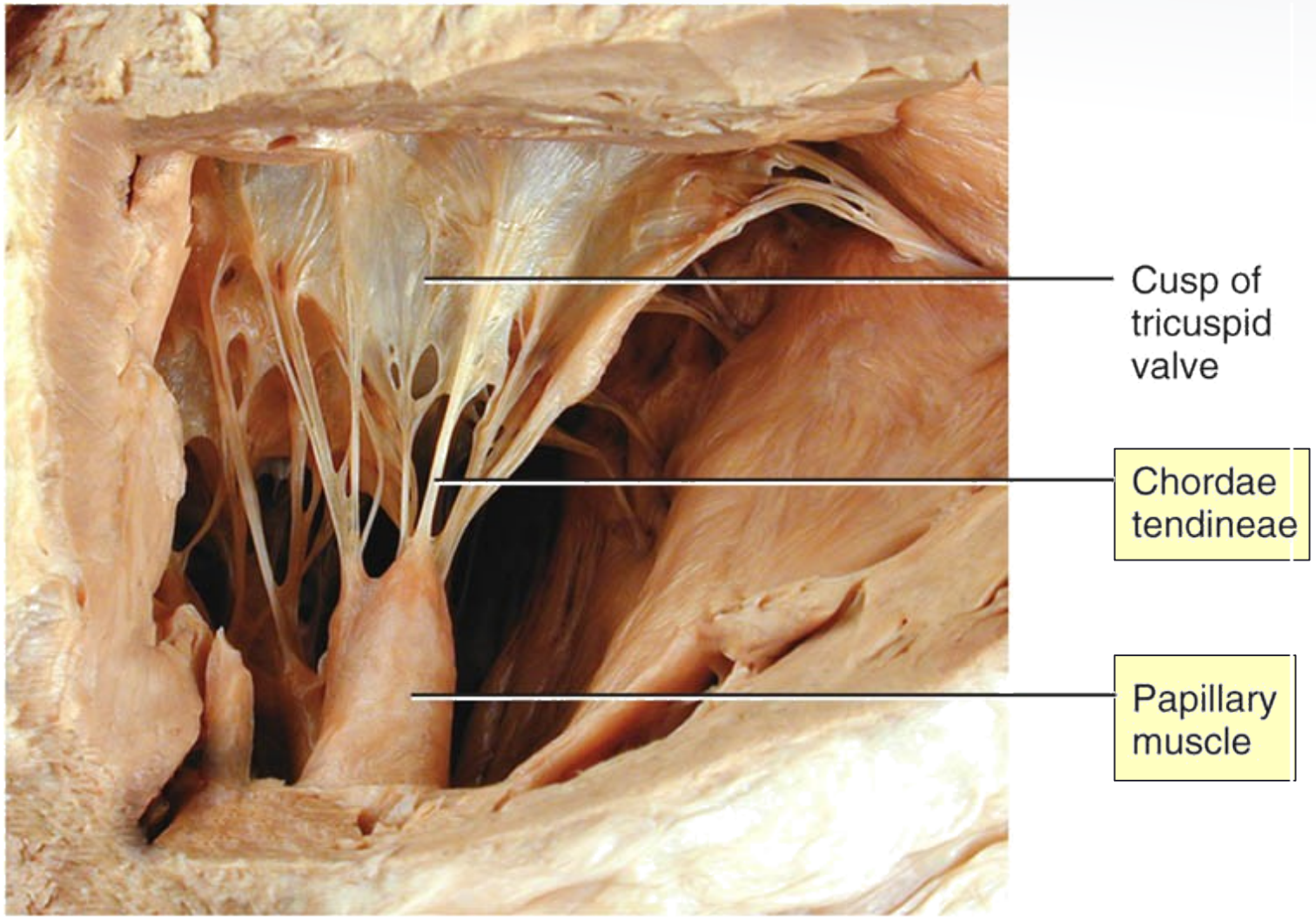
Heart Valves



Heart Valves

- As the ventricles start contracting, the closing AV valves are subject to strong forces. To prevent valve damage at an early age, the AV valves are tethered to the walls of the ventricles by “heart strings” (chordae tendineae) attached to papillary muscles.
- The papillary muscles pull on the AV valves via the chordae tendineae, slowing their closure and preventing trauma to the valves.

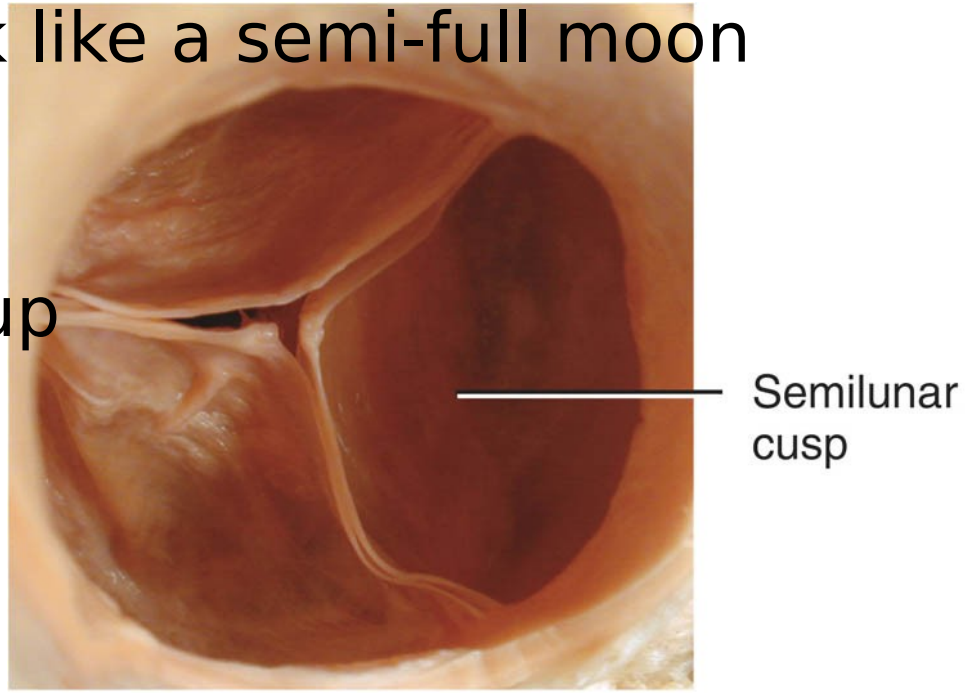
Heart Valves



(c) Tricuspid valve open

Valves

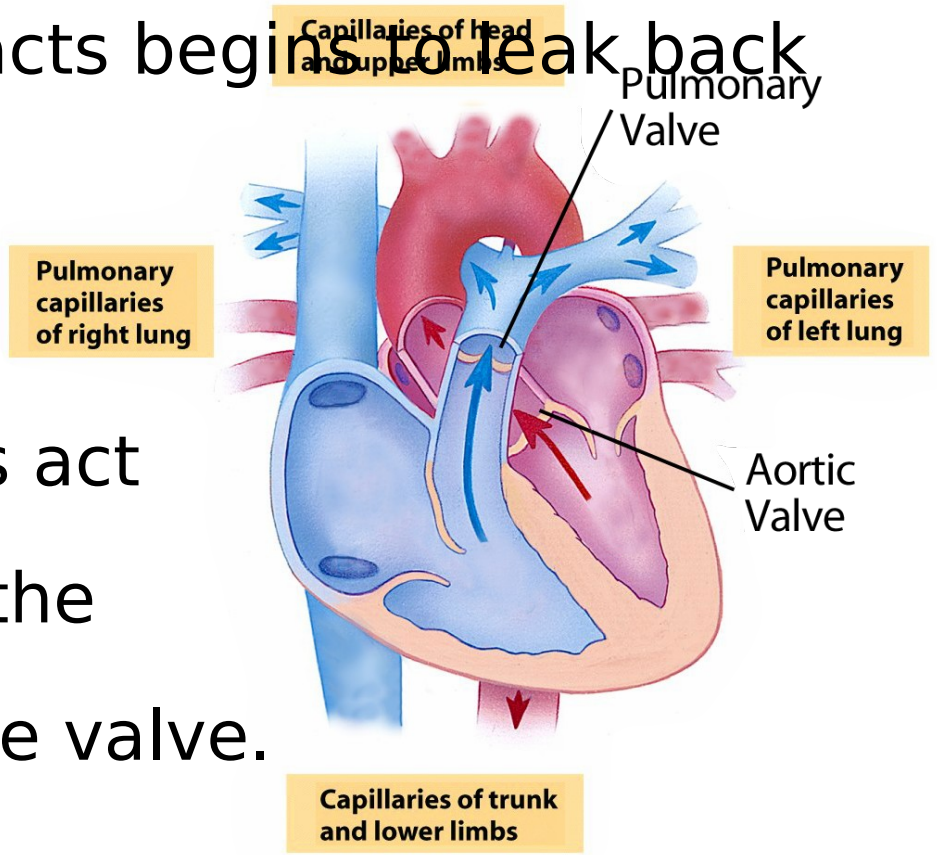
- In contrast to the delicate, leafy folds of the AV valves, the Outflow valves have rather firm cusps that each look like a semi-full moon (semilunar).
  - Each cusp makes up about a third of the valve.



(g) Superior view of aortic valve

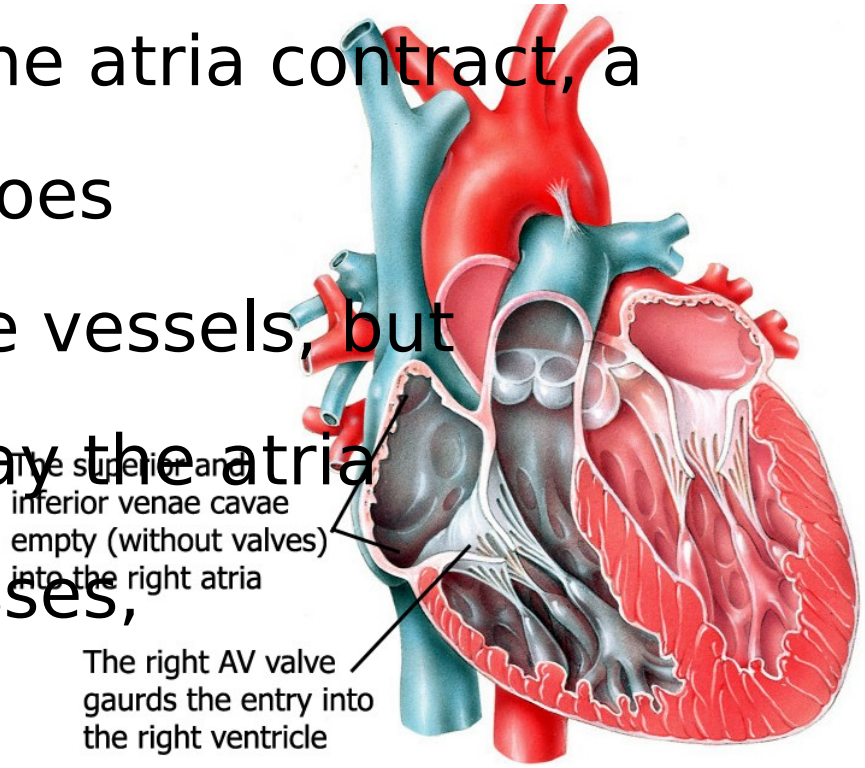
Valves

- The outflow valves open with ventricular ejection and close when blood in the aorta and pulmonary outflow tracts begins to leak back into the ventricles.
  - The semilunar cusps act like sails, catching the blood and closing the valve.



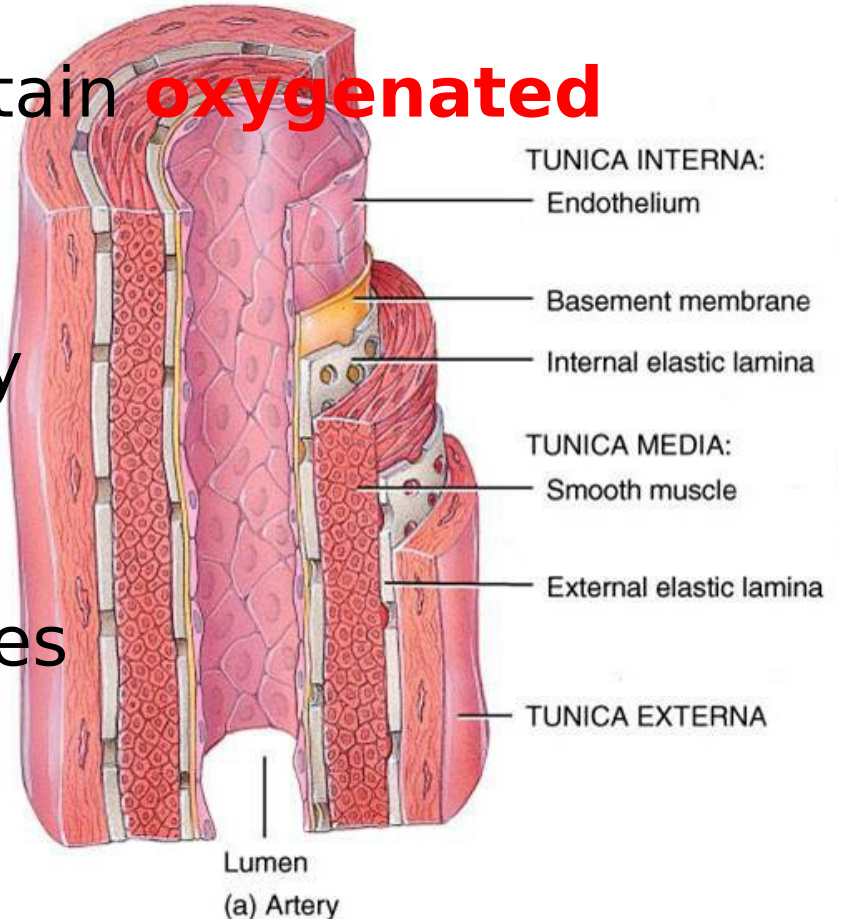
Valves

- Surprisingly, perhaps, there are no valves guarding the junction between the venae cavae and the right atrium or the pulmonary veins and the left atrium. As the atria contract, a small amount of blood does flow backward into these vessels, but it is minimized by the way the atria contract, which compresses, and nearly collapses the



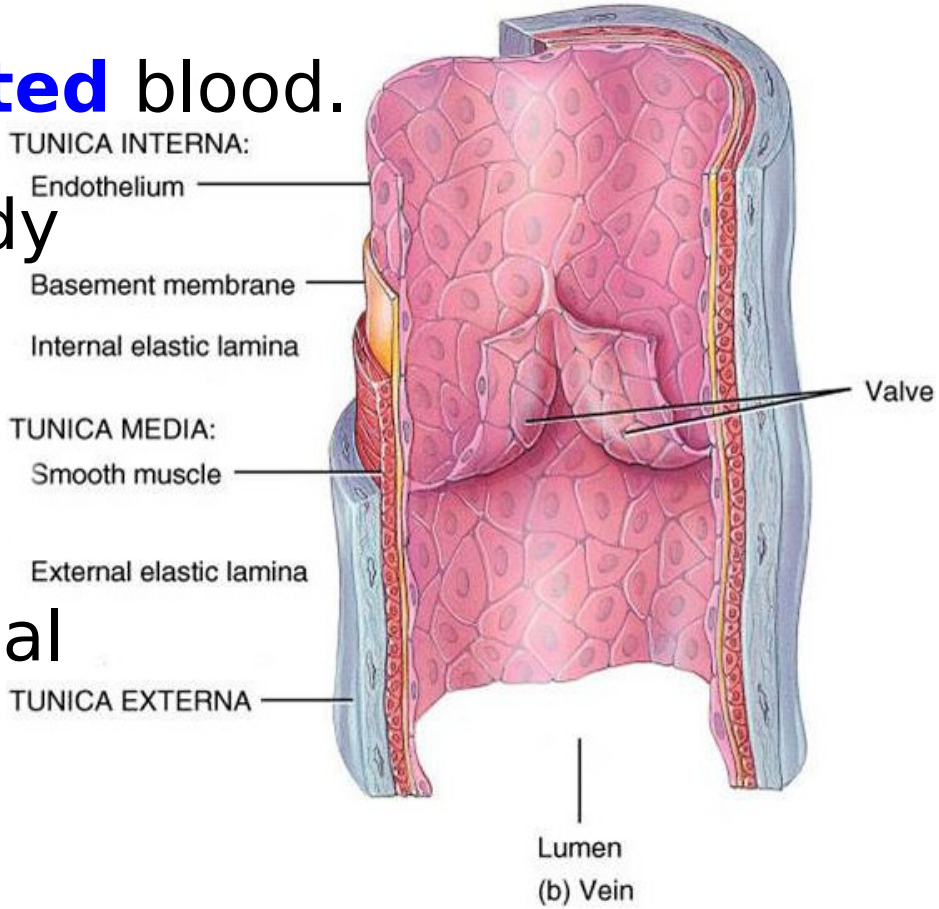
Arteries and Veins

- **Arteries** are vessels that always conduct blood away from the heart – with just a few exceptions, arteries contain **oxygenated** blood.
- Most arteries in the body are thick-walled and exposed to high pressures and friction forces.



Arteries and Veins

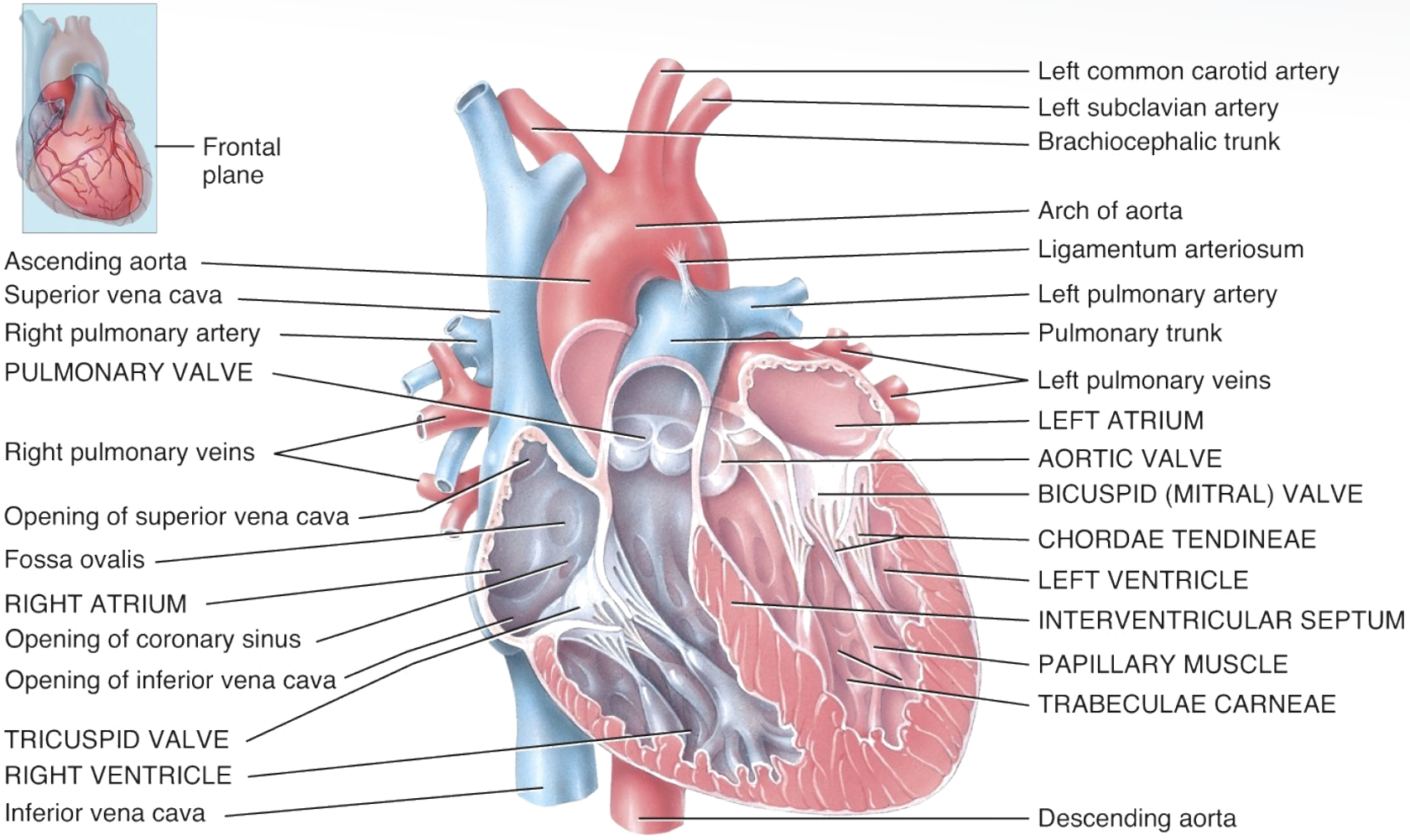
- **Veins** are vessels that always bring blood back to the heart - with just a few exceptions, veins contain **deoxygenated** blood.
- Most veins in the body are thin-walled and exposed to low pressures and minimal friction forces.



Arteries and Veins

- The **major arteries** that attach to the heart are the arch of the aorta (with its ascending and descending portions), the pulmonary trunk (with its left and right pulmonary arteries), and the coronary arteries.
- The **major veins** that attach to the heart are the superior and inferior venae cavae, the 4 pulmonary veins, and the coronary sinus (on the back of the heart).

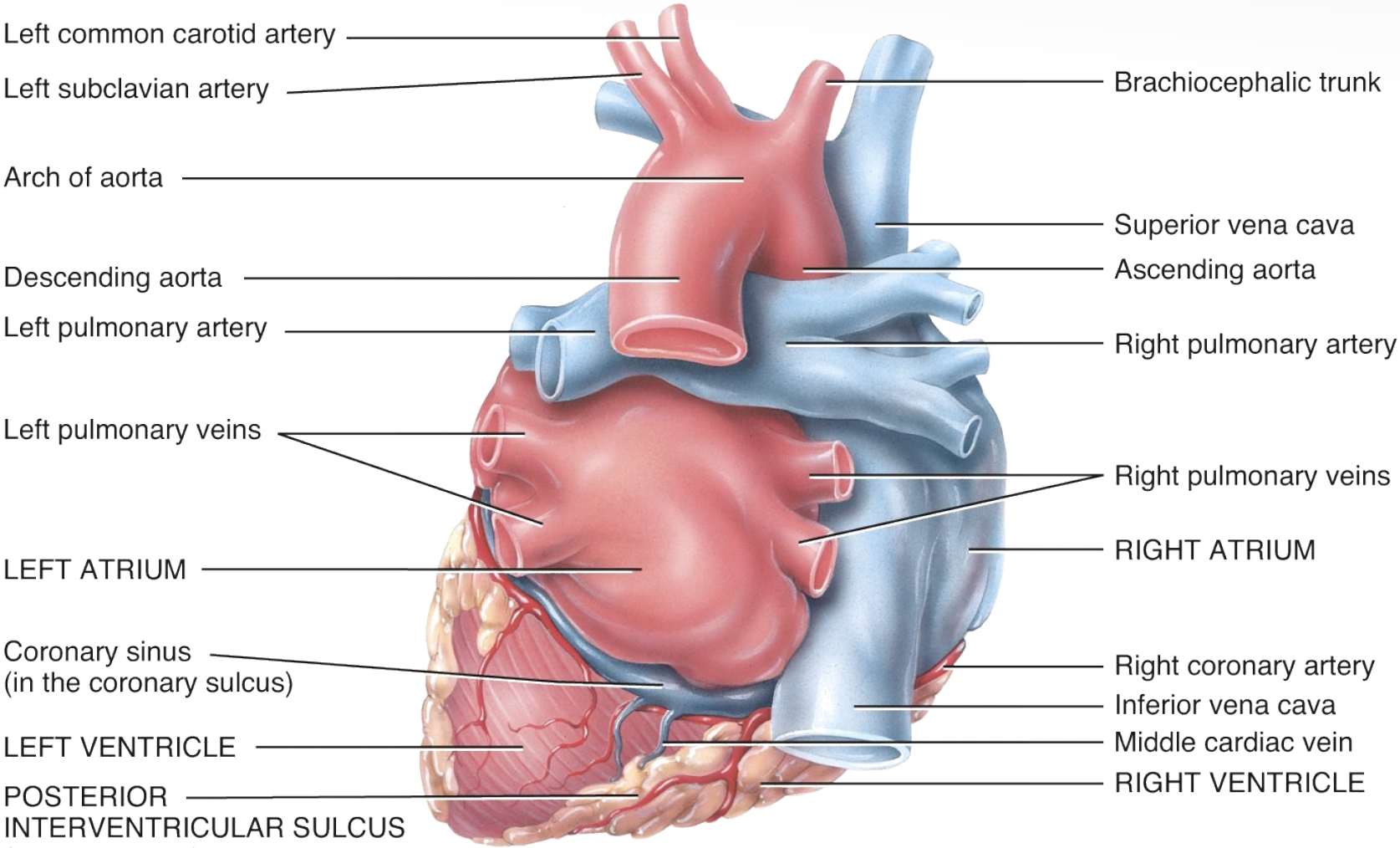
Arteries and Veins



(a) Anterior view of frontal section showing internal anatomy

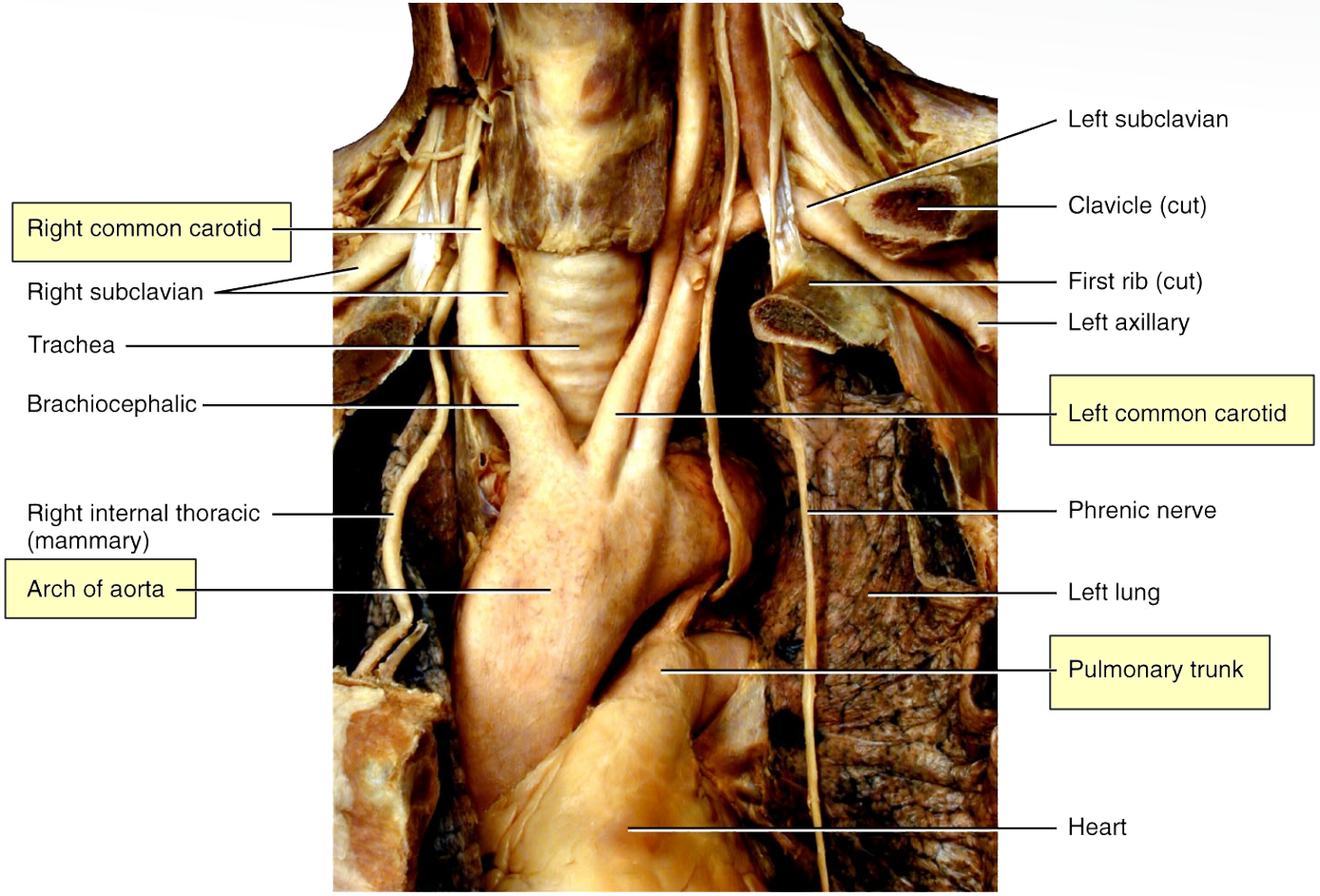
View of the front of the heart

Arteries and Veins



(c) Posterior external view showing surface features

Arteries and Veins



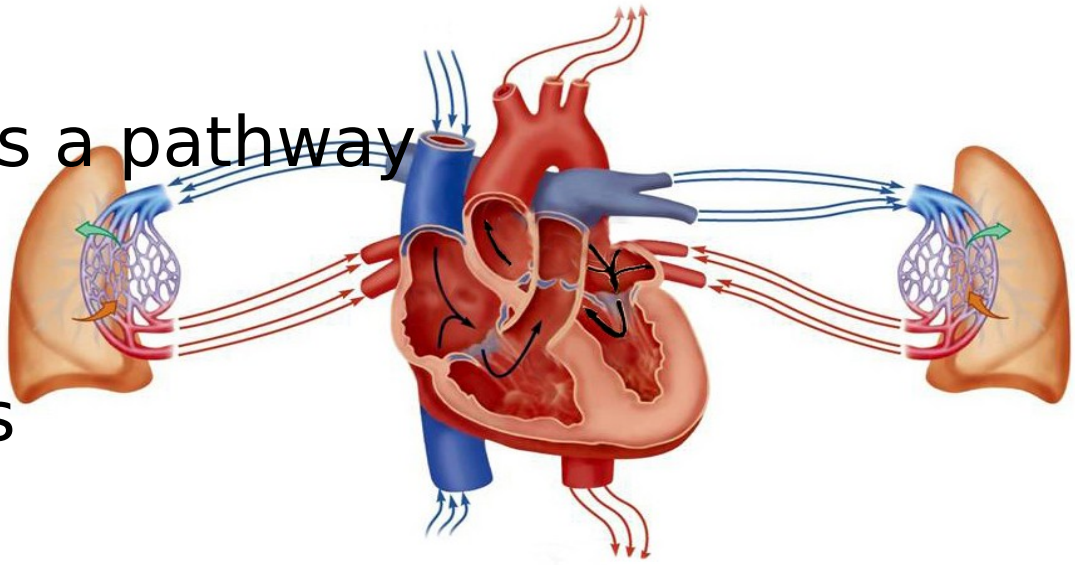
A cadaver dissection showing the major blood vessels in the anterior mediastinum

Blood Flow

- The body's blood flow can best be understood as two circuits arranged in series. The output of one becomes the input of the other:
  - **Systemic circuit** ejects blood into the aorta, systemic arteries, and arterioles and is powered by the left side of the heart.
  - **Pulmonary circuit** ejects blood into the pulmonary trunk and is powered by the right side of the heart.

Blood Flow

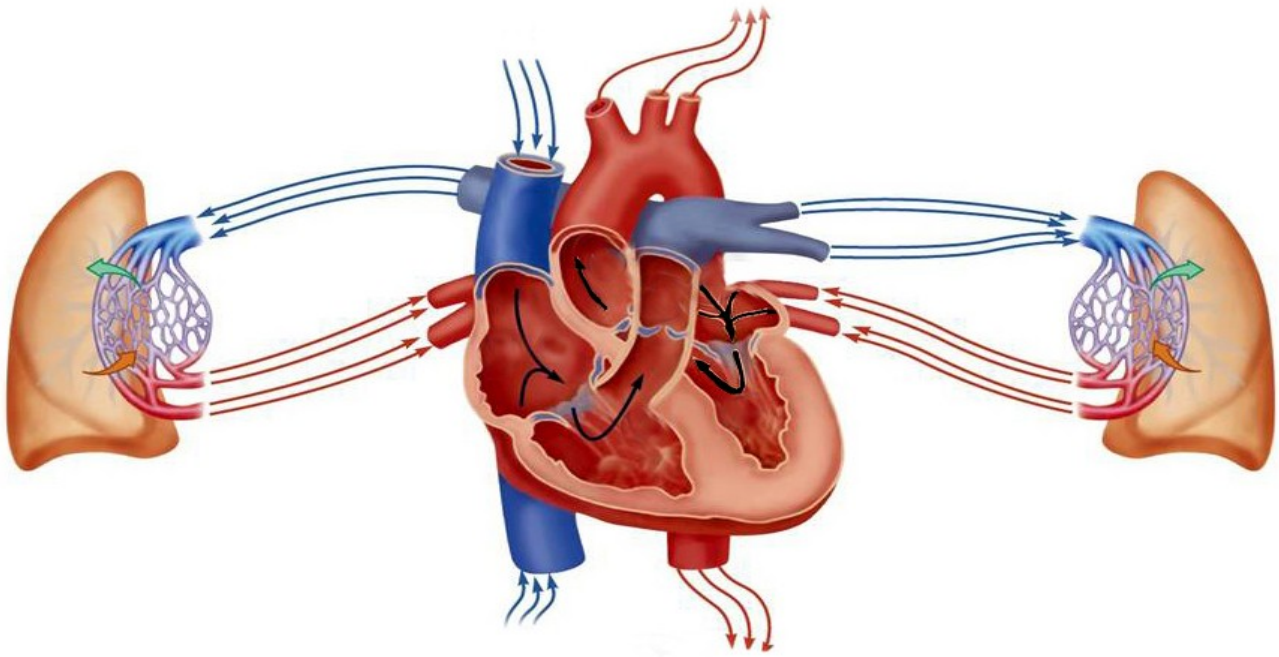
- Starting with the venous return to the heart, deoxygenated blood flows into the right atrium from 3 sources (the two vena cavae and the coronary sinus).
- Blood then follows a pathway through the right heart to the lungs to be oxygenated.



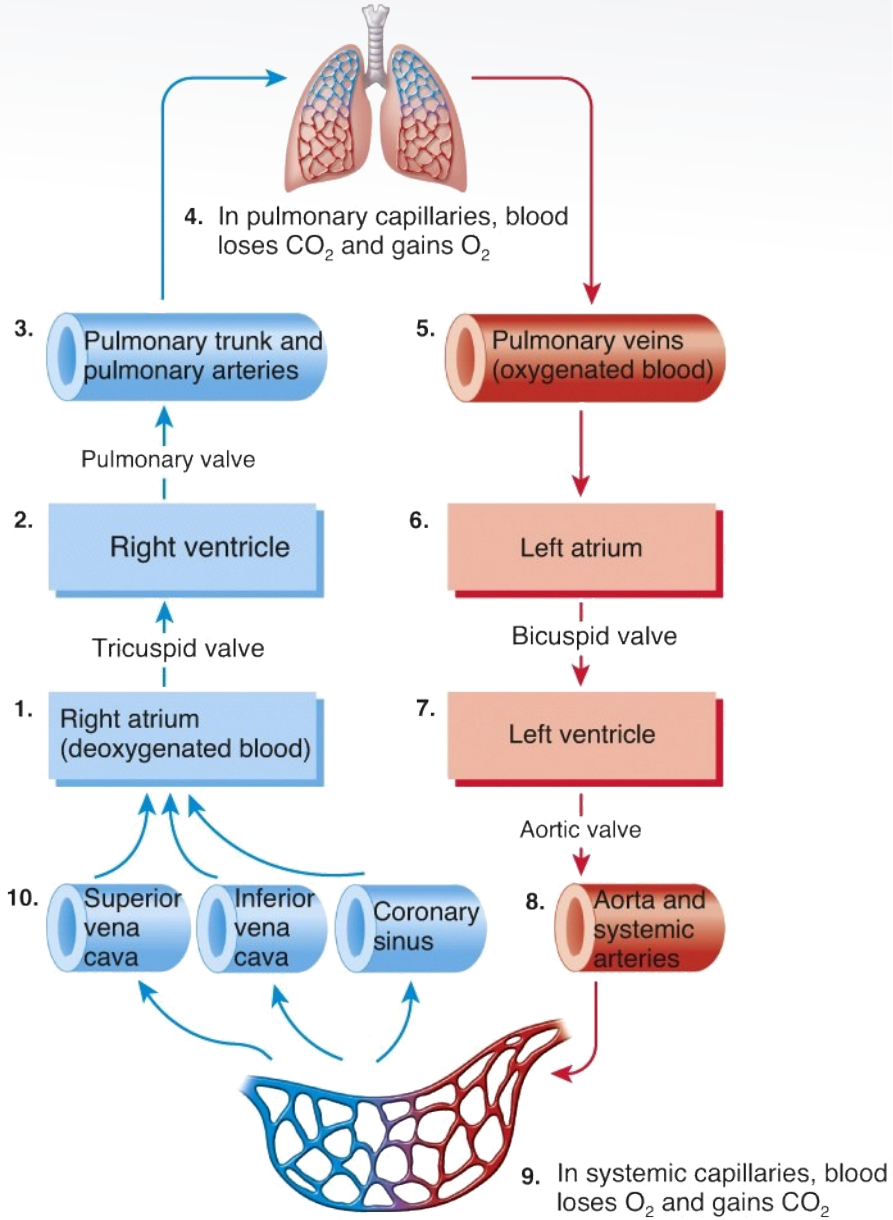
The right-sided Pulmonary Circulation

Blood Flow

- Oxygenated blood returns to the left heart to be pumped through the outflow tract of the systemic circulation.



The left-sided Systemic Circulation



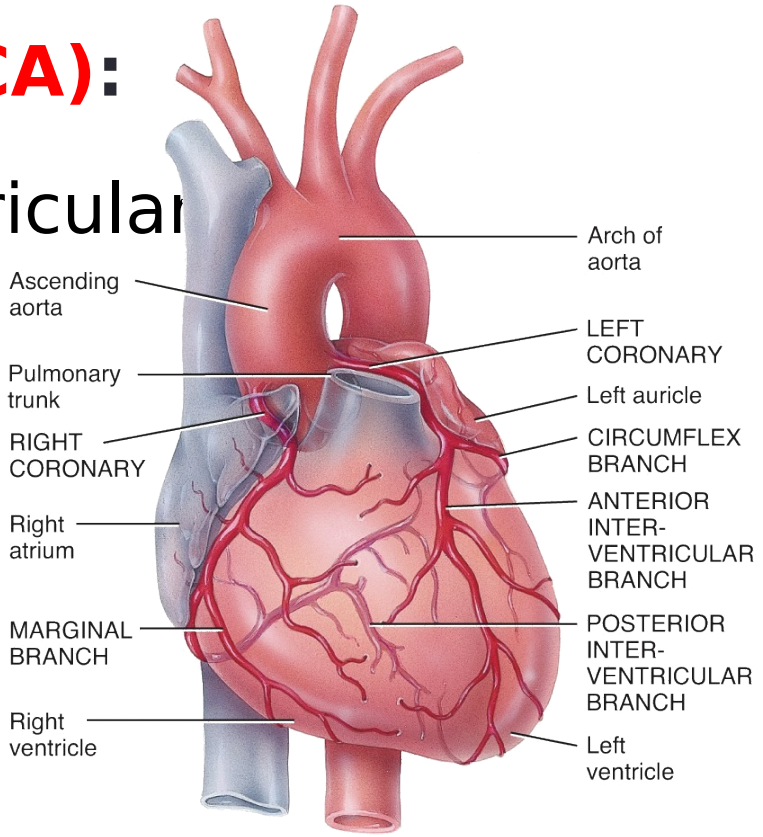
(b) Diagram of blood flow

Coronary Vessels

- Only the innermost tissues lining the chambers of the heart can derive oxygen from the blood flowing through those chambers.
  - The myocardium (and other tissues of the thick cardiac walls) must get nutrients from blood flowing through the **coronary circulation**.
  - Even then, only during the relaxation phase of ventricular diastole, will blood actually flow through the coronary circulation.

Coronary Vessels

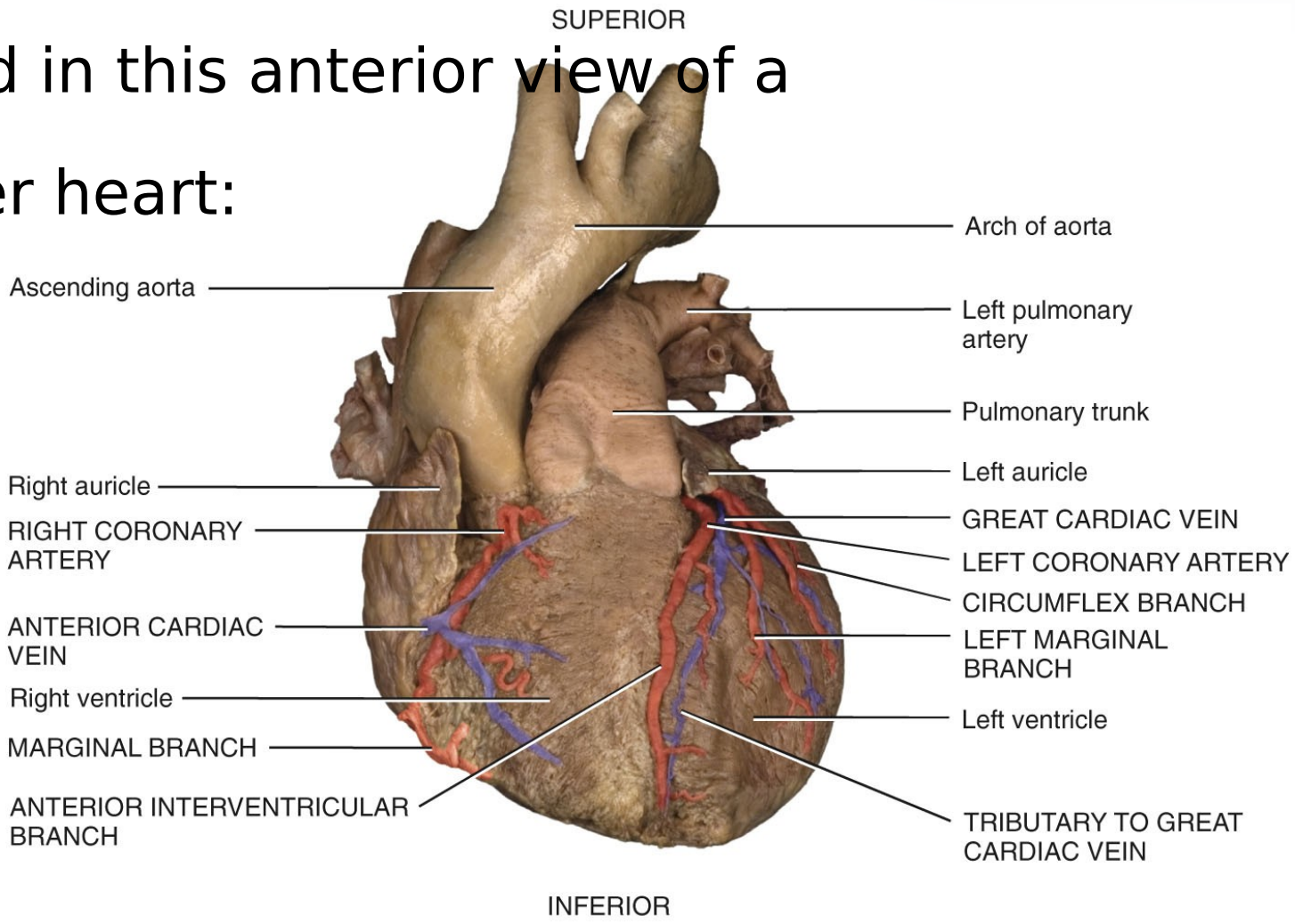
- Starting at the aortic root, the direction of blood flow is from the aorta to the left and right coronary arteries **(LCA, RCA)**:
  - LCA to anterior interventricular and circumflex branches
  - RCA to marginal and posterior atrioventricular branches



(a) Anterior view of coronary arteries

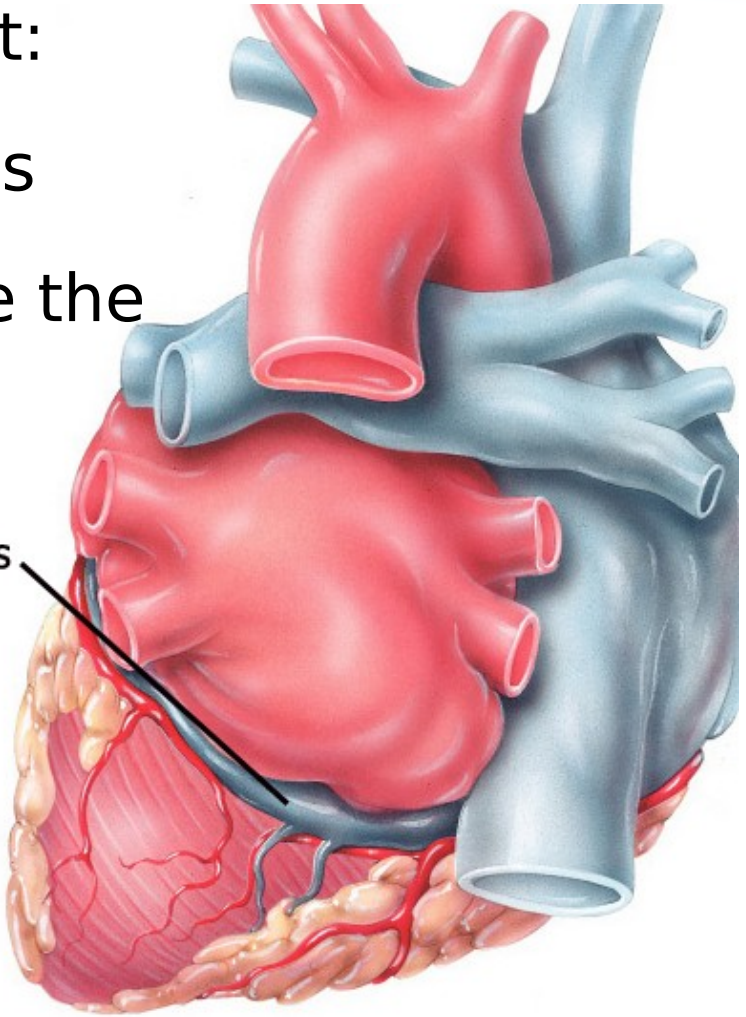
Coronary Vessels

- The coronary arteries and veins have been painted in this anterior view of a cadaver heart:



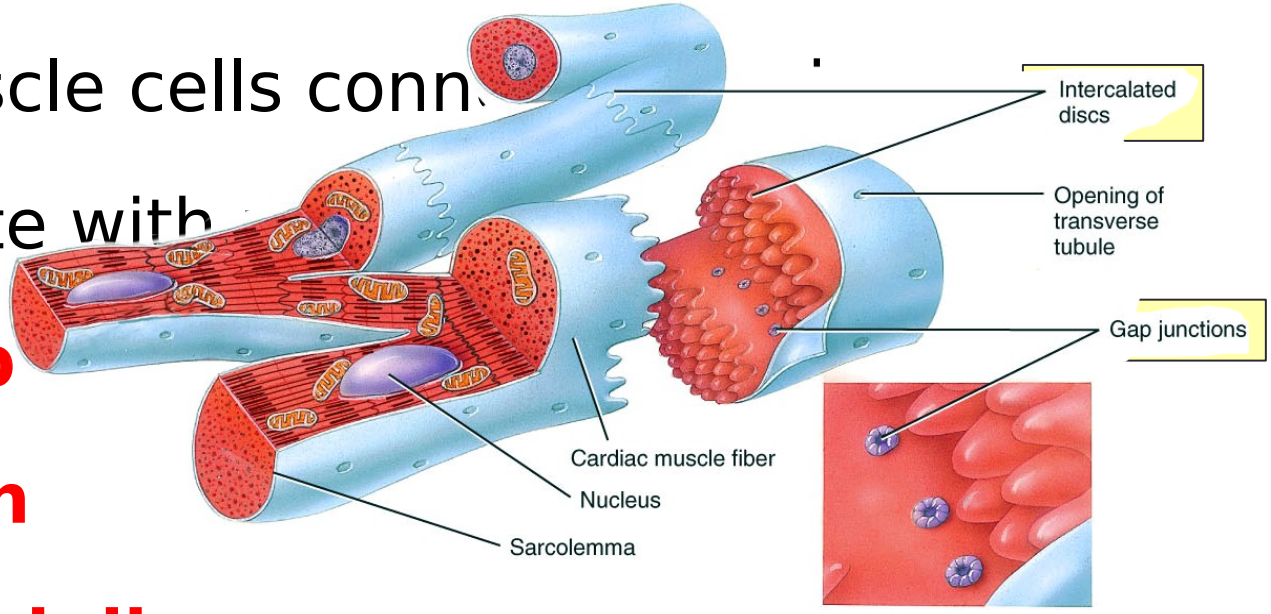
Coronary Vessels

- **Coronary veins** all collect into the coronary sinus on the back part of the heart:
  - The coronary sinus empties into the right atrium where the deoxygenated coronary blood joins with oxygen-depleted blood from the rest of the body.



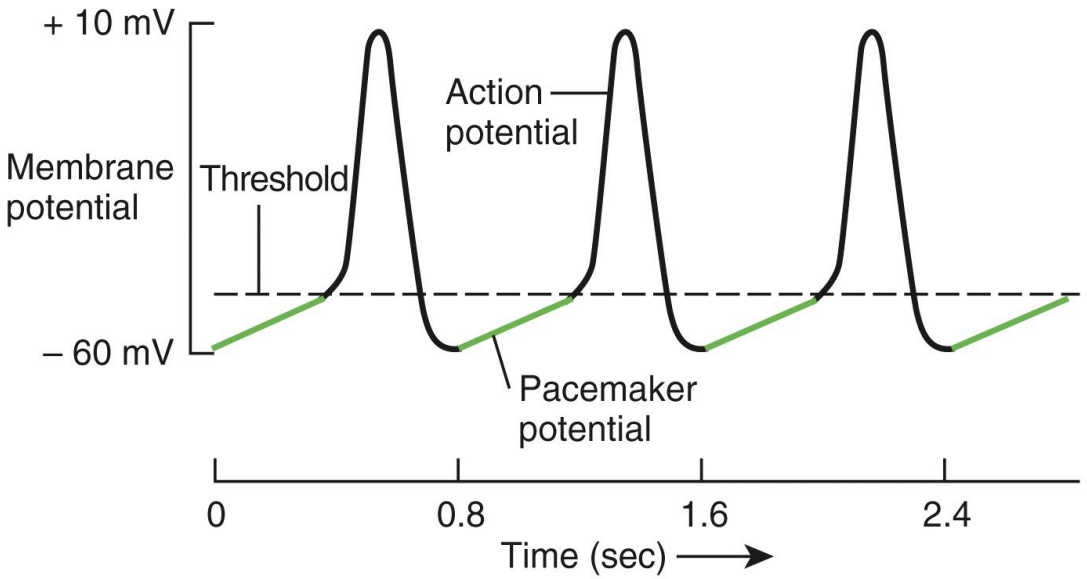
Cardiac Muscle Tissue

- Cardiac muscle, like skeletal muscle, is striated. Unlike skeletal muscle, its fibers are shorter, they branch, and they have only one (usually centrally located) nucleus.
- Cardiac muscle cells conn. . communicate with through **gap junctions in intercalated discs.**



Autorhythmicity

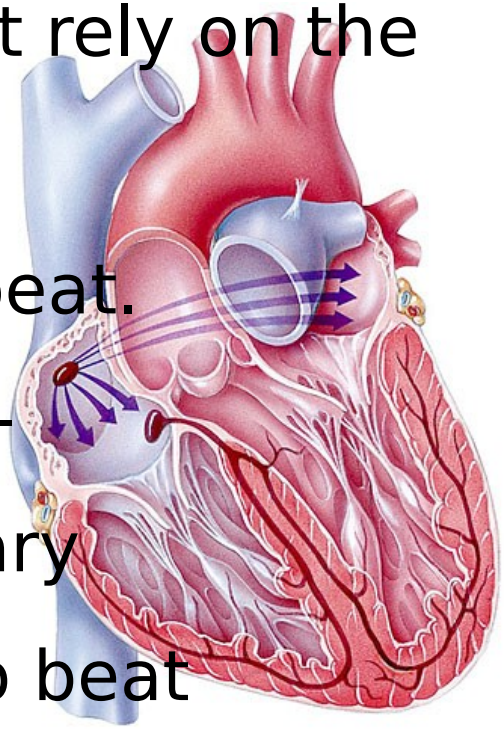
- During embryonic development, about 1% of all of the muscle cells of the heart form a network or pathway called the **cardiac conduction syst** of **myocytes** is unusual in that they have the ab to spontaneously depolarize.



(b) Pacemaker potentials and action potentials in autorhythmic fibers of SA node

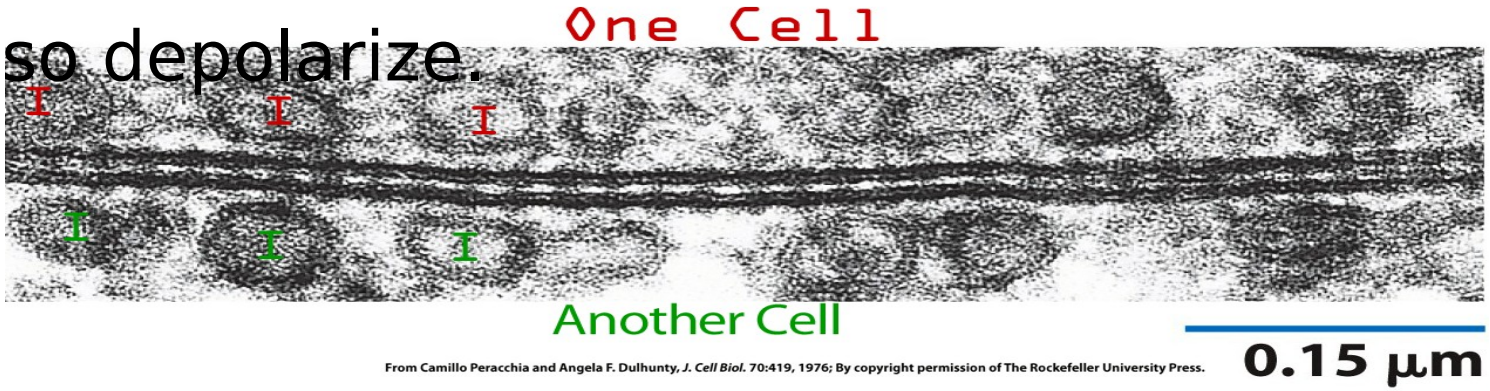
Autorhythmicity

- The rhythmical electrical activity they produce is called **autorhythmicity**. Because heart muscle is autorhythmic, it does not rely on the central nervous system to sustain a lifelong heartbeat.
  - When transplanted hearts are re-warmed following cardiopulmonary bypass, they once again begin to beat without the need to connect outside nerves or use life-long pacemaker devices



Autorhythmicity

- Autorhythmic cells spontaneously depolarize at a given rate, some groups faster, some groups slower. Once a group of autorhythmic cells reaches threshold and starts an action potential (AP), all of the cells in that area of the heart also depolarize.

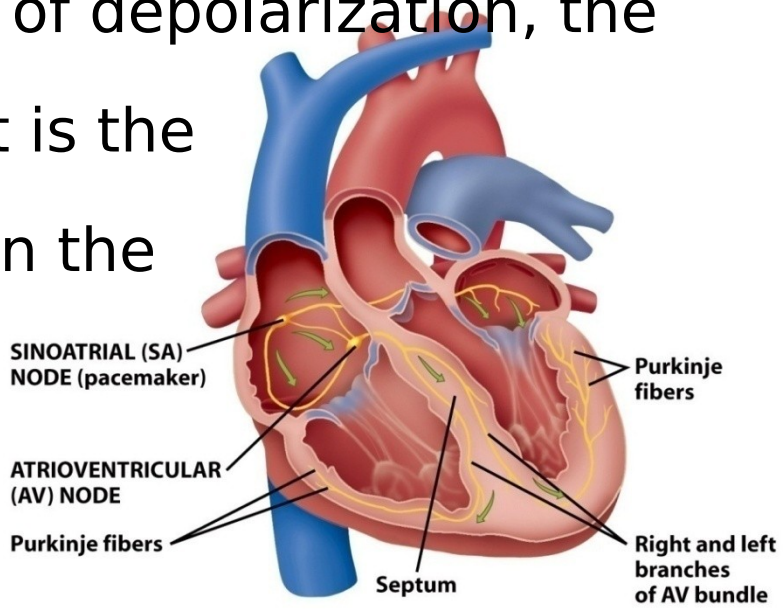


From Camillo Peracchia and Angela F. Dulhunty, *J. Cell Biol.* 70:419, 1976; By copyright permission of The Rockefeller University Press.

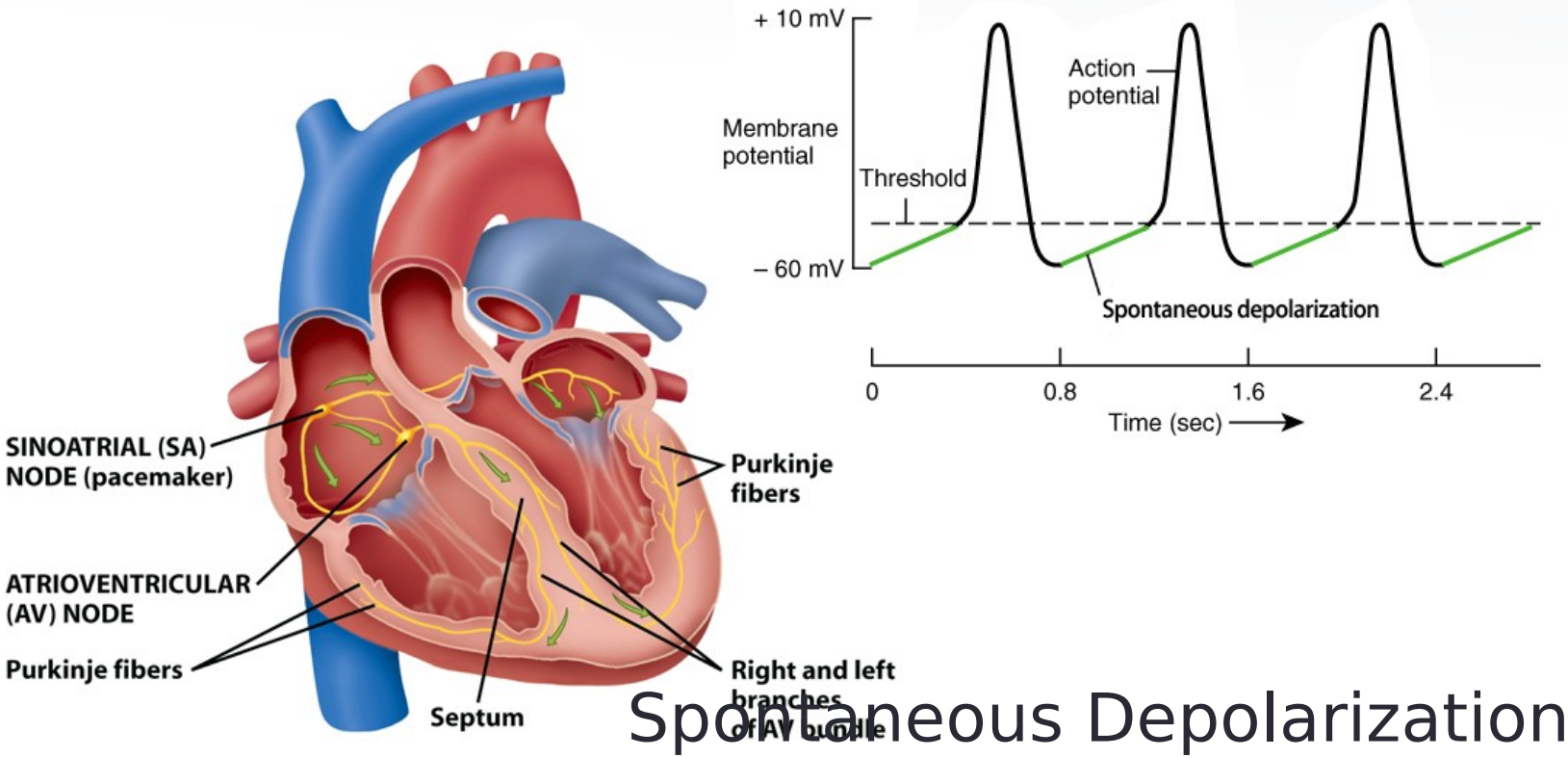
Membrane of two cells clearly seen. The spread of ions through gap junctions of the Intercalated discs (I) allows the AP to pass from cell to cell.

Cardiac Conduction

- The self-excitable myocytes that "act like nerves" have the 2 important roles of **forming the conduction system** of the heart and **acting as pacemakers** within that system.
- Because it has the fastest rate of depolarization, the normal pacemaker of the heart is the sinoatrial **(SA) node**, located in the right atrial wall just below where the superior vena cava enters the chamber.



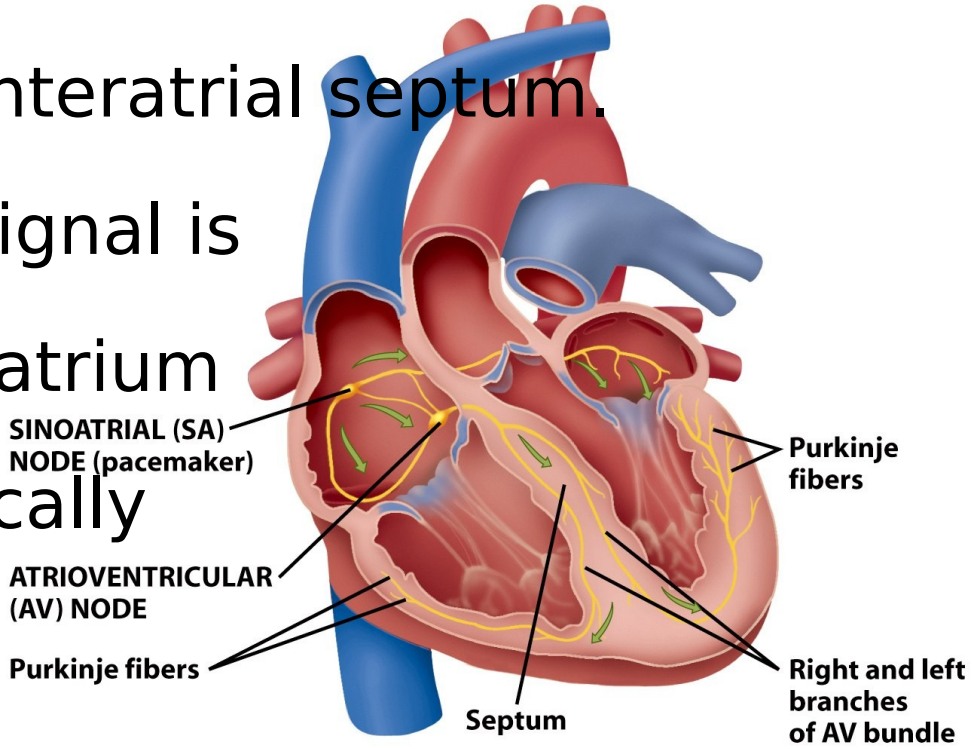
Cardiac Conduction



Spontaneous Depolarization of autorhythmic fibers in the SA node firing about once every 0.8 seconds, or 75 action potentials per minute

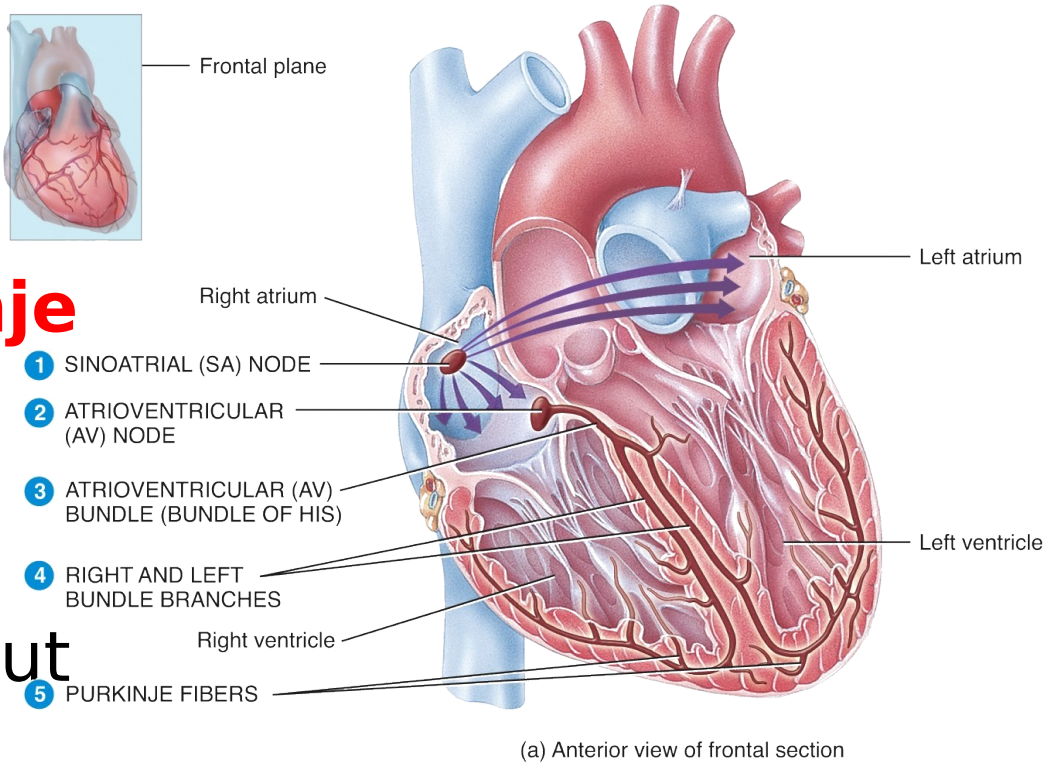
Cardiac Conduction

- The action potential generated from the SA node reaches the next pacemaker by propagating throughout the wall of the atria to the **AV node** in the interatrial septum.
- At the AV node, the signal is slowed, allowing the atrium a chance to mechanically move blood into the ventricles.



Cardiac Conduction

- From the AV node, the signal passes through the **AV bundle to the left and right bundle branches** in the interventricular septum towards the apex of the heart.
- Finally, the **Purkinje fibers** rapidly conduct the action potential throughout the ventricles (0.2 seconds after atrial contraction)



(a) Anterior view of frontal section

Frontal plane

Left atrium

Right atrium

1 SINOATRIAL (SA) NODE

2 ATRIOVENTRICULAR (AV) NODE

3 ATRIOVENTRICULAR (AV) BUNDLE (BUNDLE OF HIS)

4 RIGHT AND LEFT BUNDLE BRANCHES

Left ventricle

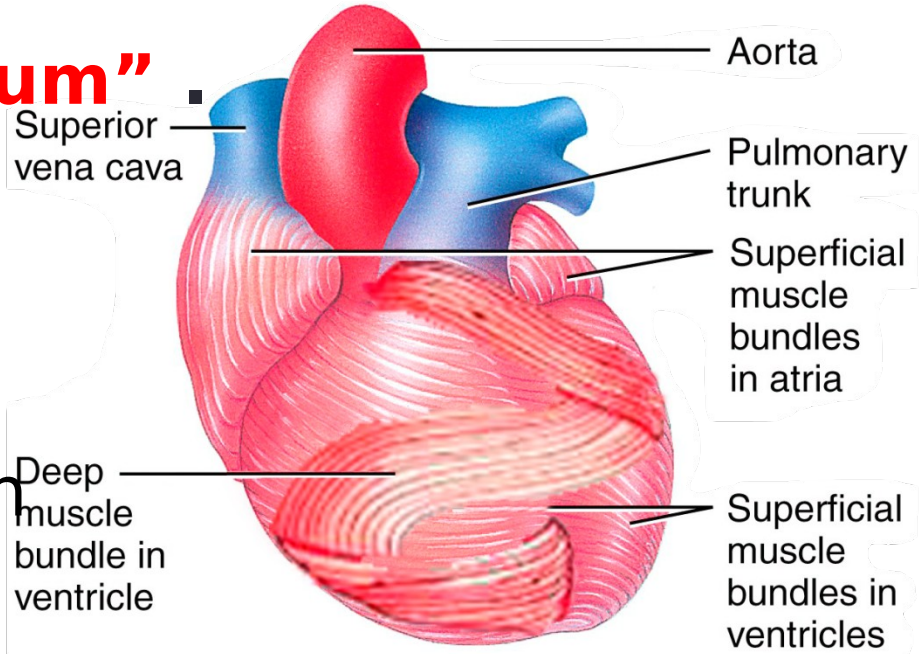
Right ventricle

5 PURKINJE FIBERS

Anterior view of frontal section

Coordinating Contractions

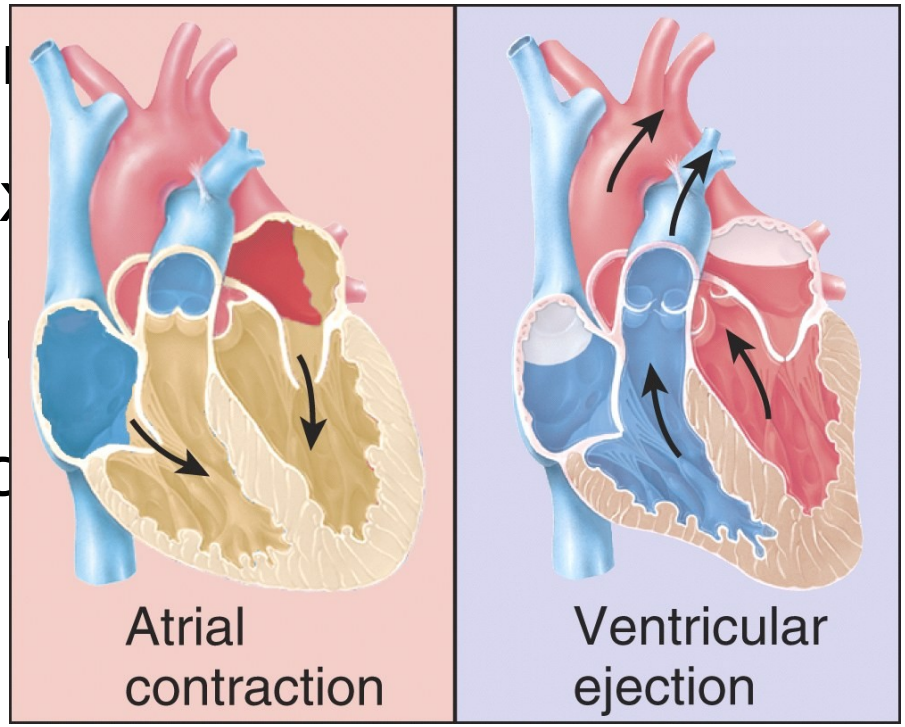
- Although anatomically the heart consist of individual cells, the bands of muscle wind around the heart and work as a unit – forming a **“functional syncytium”** .
  - This allows the top and bottom parts to contract in their own unique way.



Cardiac muscle bundles of the myocardium

Coordinating Contractions

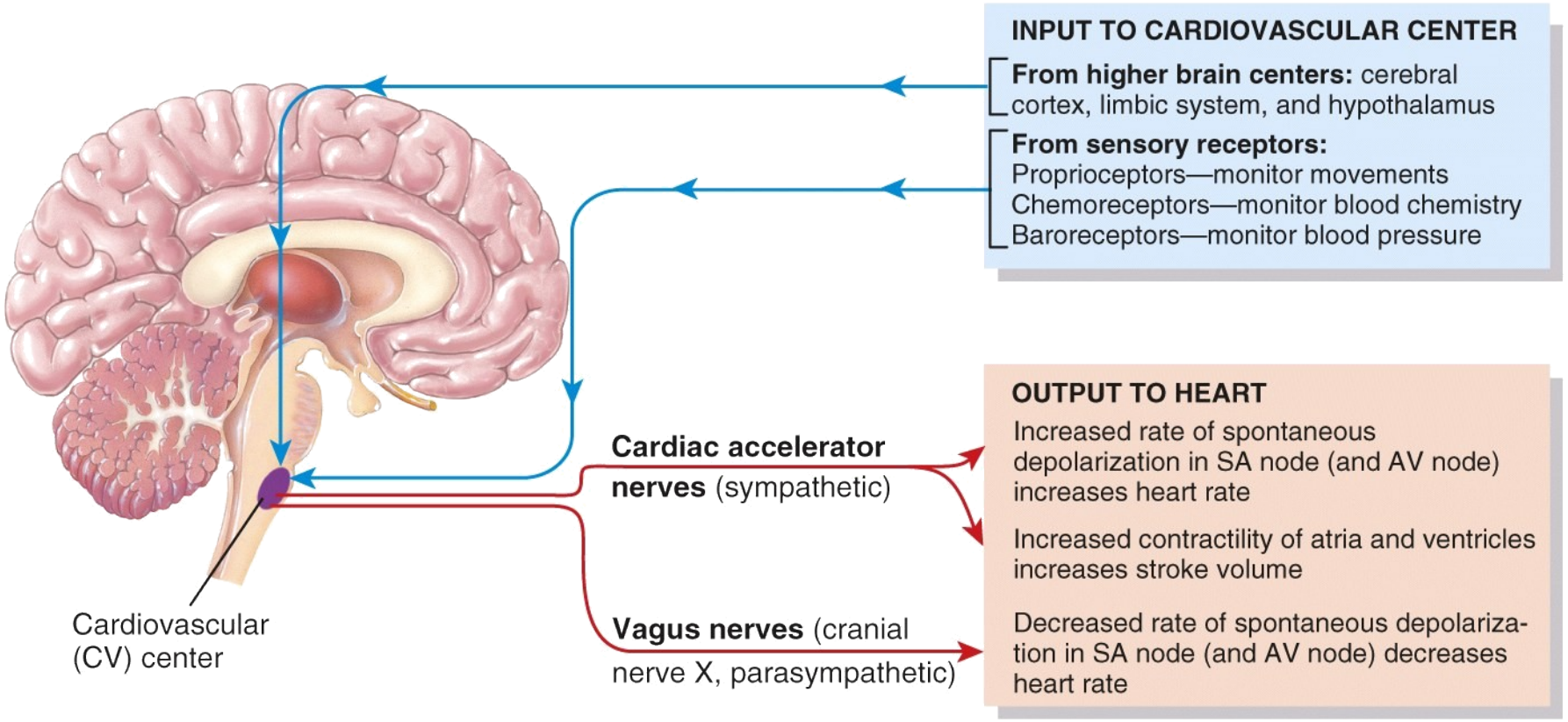
- The atrial muscle syncytium contracts as a single unit to force blood down into the ventricles.
- The syncytium of ventr
  contracting at the apex
  squeezing blood upwar
  to exit the outflow trac



ANS Innervation

- Although the heart does not rely on outside nerves for its basic rhythm, there is abundant **sympathetic** and **parasympathetic** innervation which alters the rate and force of heart contractions.
  - The role of autonomic nervous system input is to regulate changes in blood pressure, blood flow, and blood volume to maintain enough cardiac output to provide for all

ANS Innervation

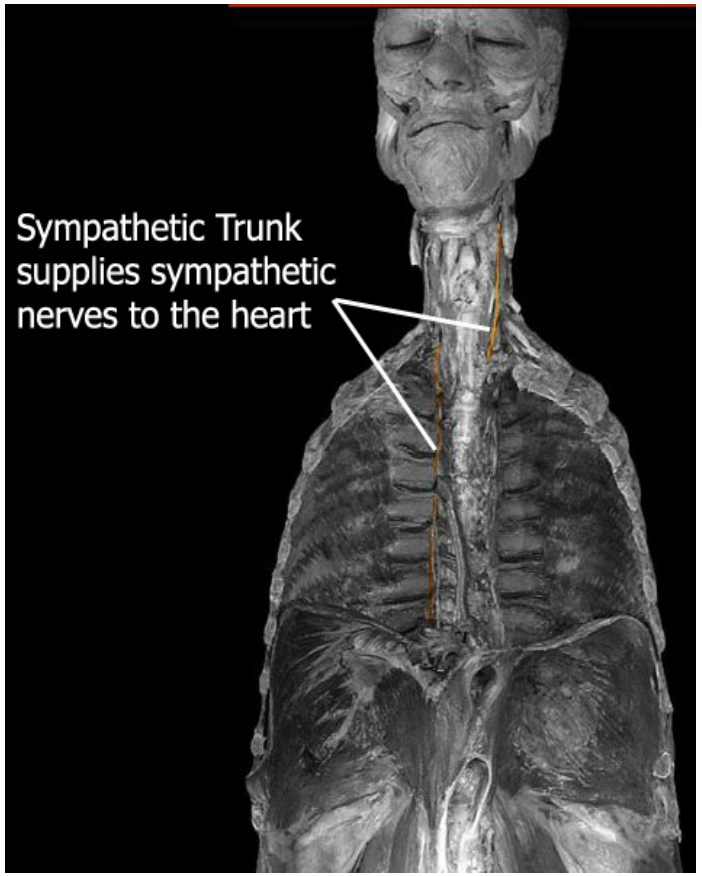


ANS Innervation

- The **cardioacceleratory center** is found in the medulla.
  - Sensory information from baroreceptors in the carotid body and in the arch of the aorta relay information about blood pressure and blood flow to the cardioacceleratory center.
  - In response, sympathetic fibers pass through the spinal cord to enter the sympathetic ganglia located near the thoracic region of the spinal column. They leave the sympathetic

ANS Innervation

- Sympathetic nerves are present throughout the atria (especially in the SA node) and ventricles.
  - Sympathetic activity increases the heart rate and the strength of myocardiac contraction to increase blood flow



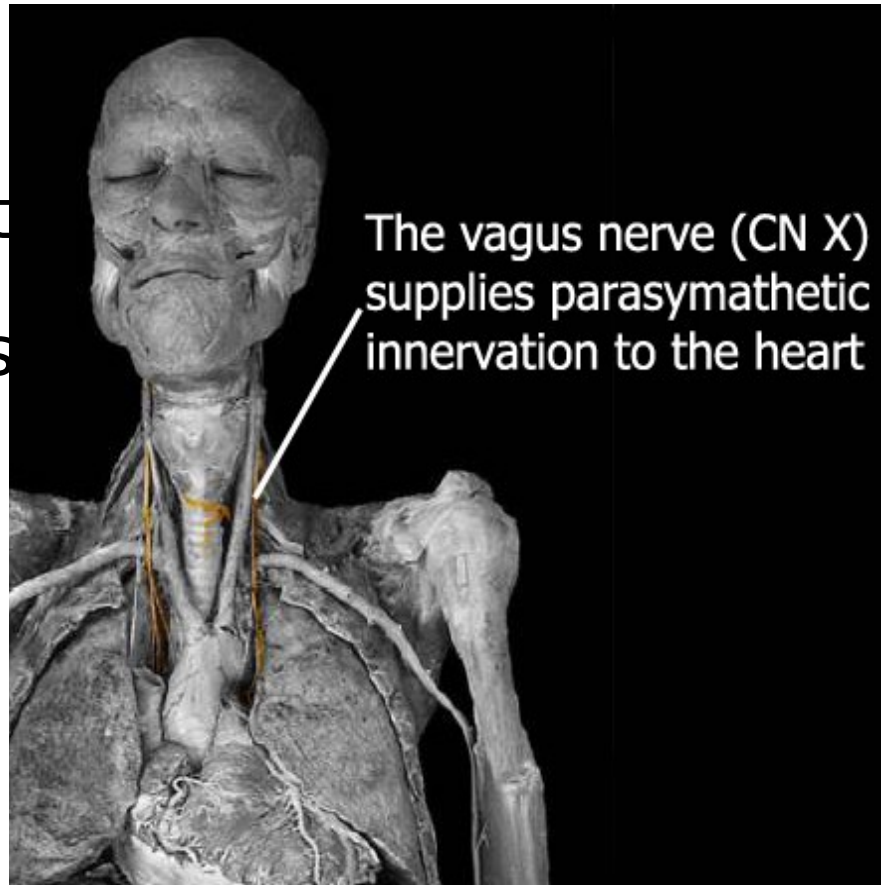
Real Anatomy. Although the small sympathetic nerves are difficult to see on the heart, they all arise from these major paravertebral sympathetic chains.

ANS Innervation

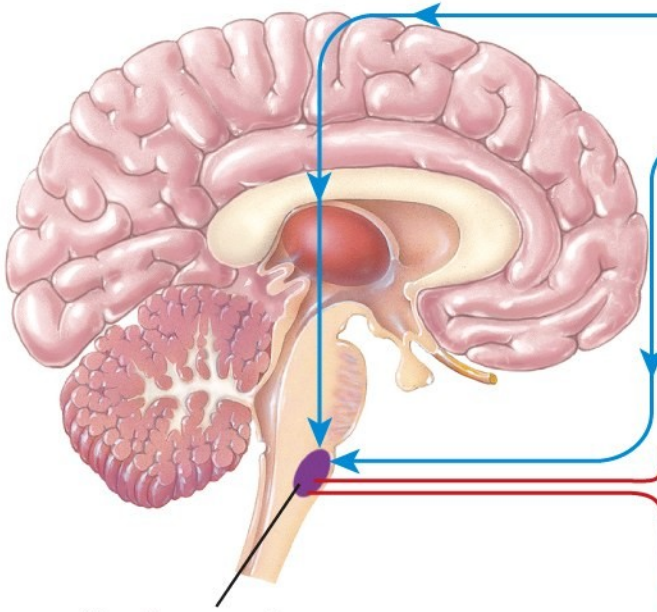
- The medulla also contains the cell bodies of the neurons that make up the **cardioinhibitory center**:
  - The same sensory information coming in from peripheral baroreceptors goes to this area as well.
  - When stimulated, parasympathetic fibers in CN X, the vagus nerve, release acetylcholine that decreases the heart rate and strength of contraction.

ANS Innervation

- In this photograph from Real Anatomy, the right and left vagus nerves are seen exiting the skull.
- Parasympathetic activit slows the heart from its native rate of 100 bpm to about 70-80 in the average adult.



ANS Innervation



Cardiovascular (CV) center

Cardiac accelerator nerves (sympathetic)

Vagus nerves (cranial nerve X, parasympathetic)

INPUT TO CARDIOVASCULAR CENTER

From higher brain centers: cerebral cortex, limbic system, and hypothalamus

From sensory receptors:
Proprioceptors—monitor movements
Chemoreceptors—monitor blood chemistry
Baroreceptors—monitor blood pressure

OUTPUT TO HEART

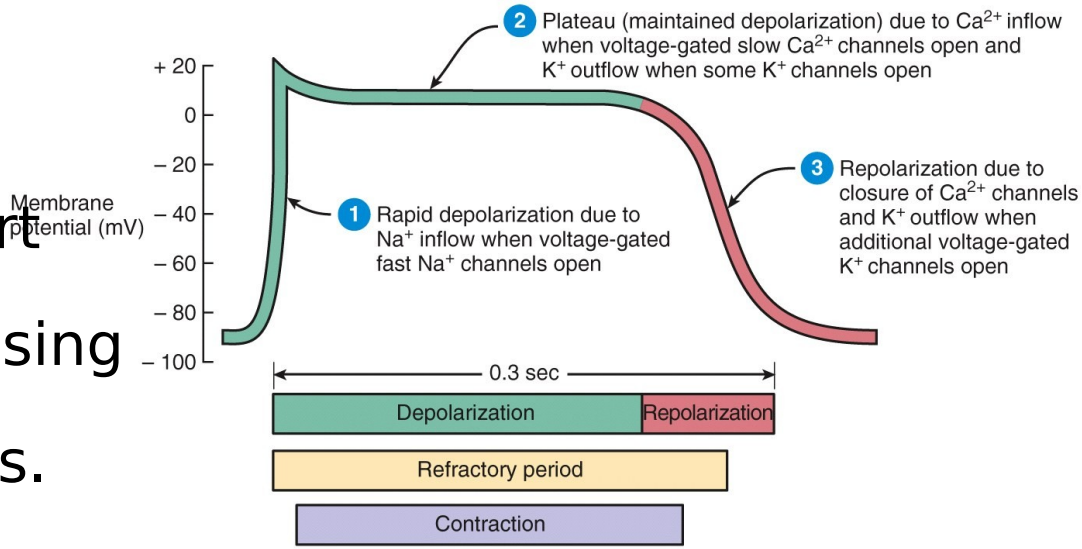
Increased rate of spontaneous depolarization in SA node (and AV node) increases heart rate

Increased contractility of atria and ventricles increases stroke volume

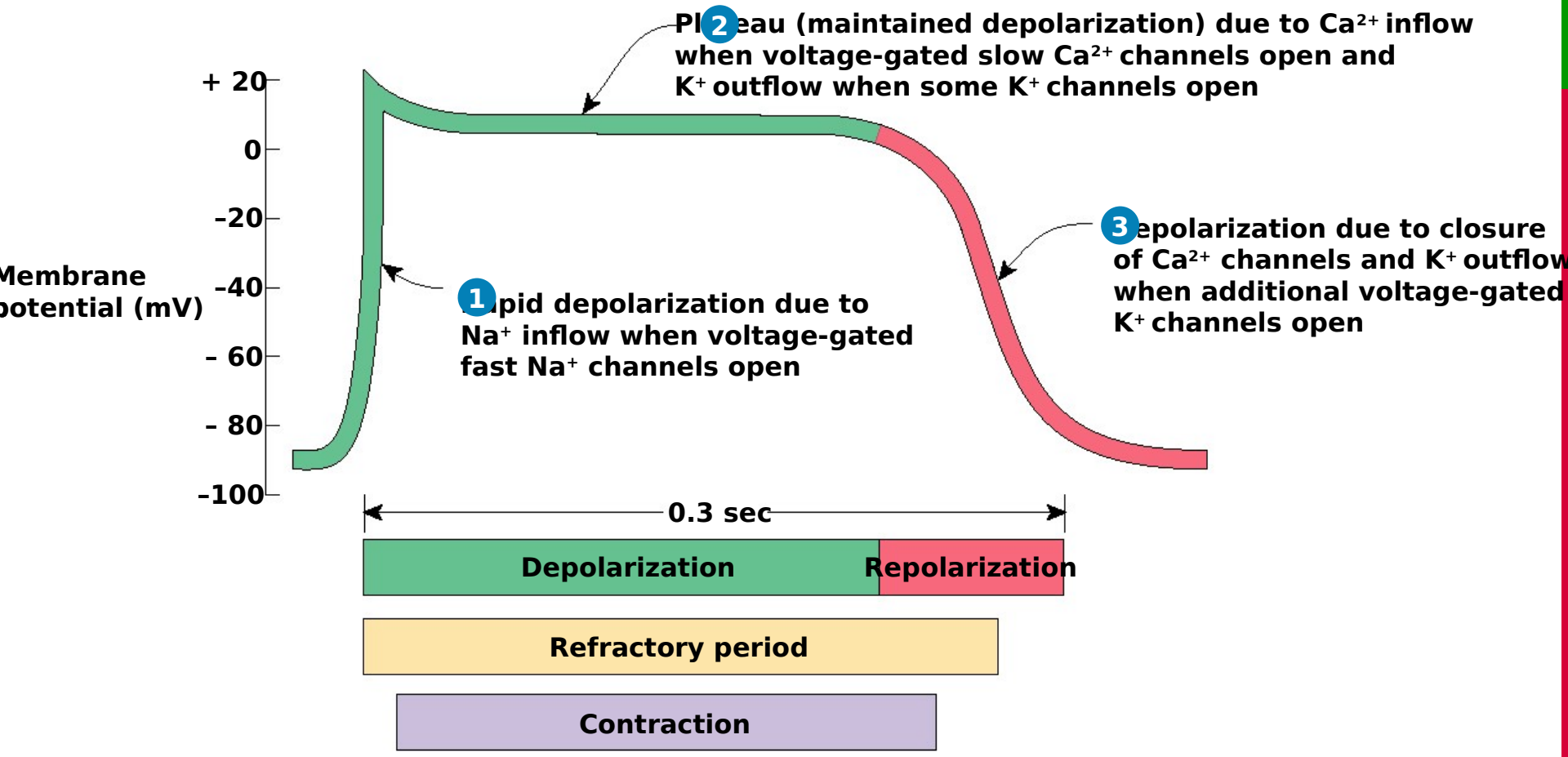
Decreased rate of spontaneous depolarization in SA node (and AV node) decreases heart rate

Cardiac Muscle Action Potential

- The action potential (AP) initiated by the SA node travels through the conduction system to excite the “working” contractile muscle fibers in the atria and ventricles.
- Unlike autorhythmic fibers, contractile fibers have a stable RMP of –90mV.
  - The AP propagates throughout the heart by opening and closing Na^+ and K^+ channels.



Cardiac Muscle Action Potential



Cardiac Muscle Action Potential

- Unlike skeletal muscle, the refractory period in cardiac muscle lasts longer than the contraction itself - another contraction cannot begin until relaxation is well underway.
- For this reason, tetanus (maintained contraction) cannot occur in cardiac muscle, leaving sufficient time between contractions for the chambers to fill with blood.
- If heart muscle could undergo tetanus, blood flow would cease!

Cardiac Muscle Contraction

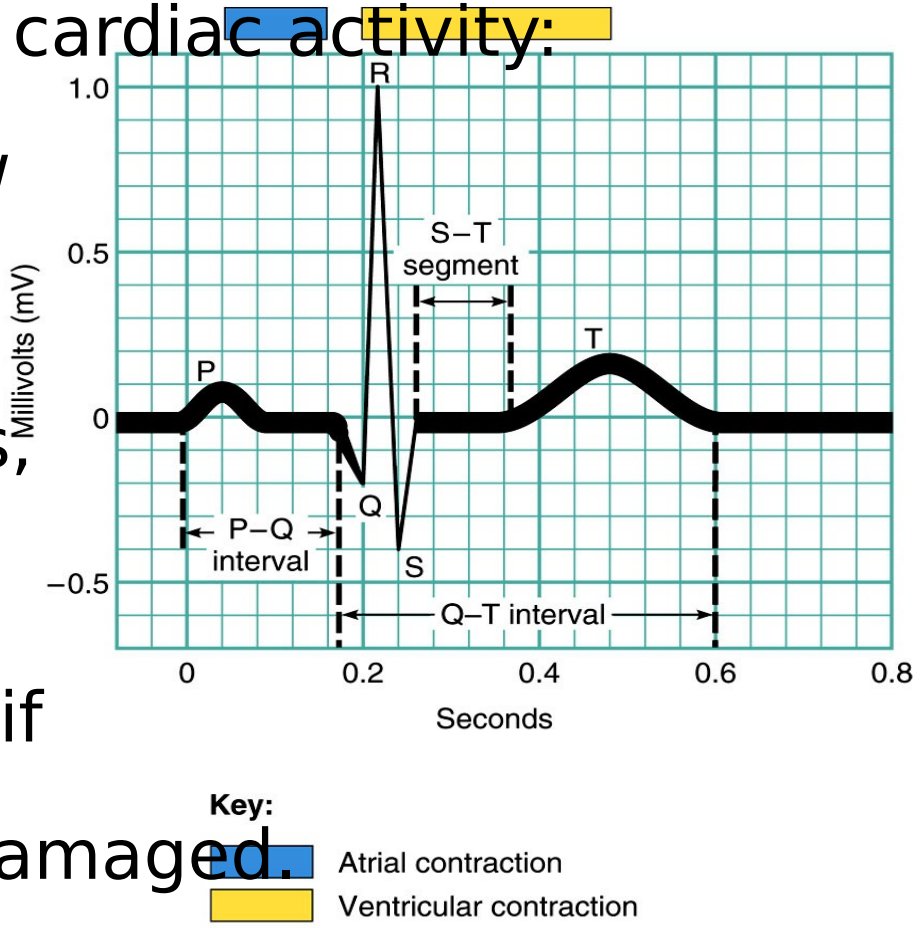
- The mechanism of contraction is similar in cardiac and skeletal muscle: Electrical activity leads to Ca^{2+} release from the SR, actin and myosin filaments go through the contraction cycle (see p. 313), and tension is developed as the filaments slide past one another.
  - Epinephrine, released by the sympathetic NS, increases contraction force by enhancing the movement of Ca^{2+} into the

The Electrocardiogram

- An ECG is a recording of the electrical changes on the surface of the body resulting from the depolarization and repolarization of the myocardium.
- ECG recordings measure the presence or absence of certain waveforms (deflections), the size of the waves, and the time intervals of the cardiac cycle.
  - By measuring the ECG, we can quantify and

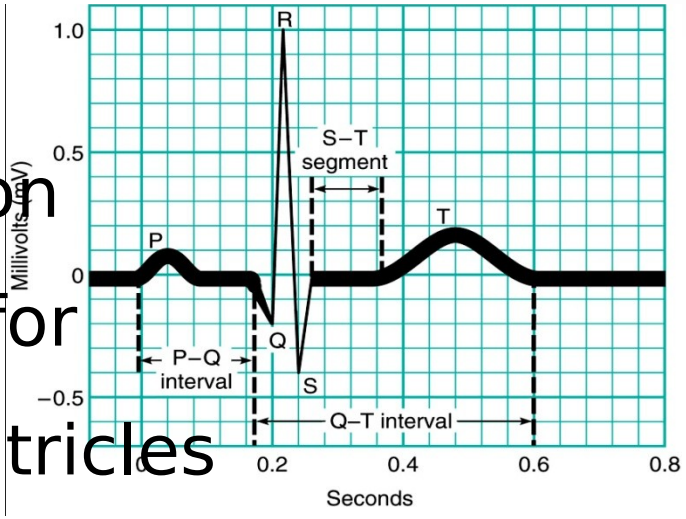
The Electrocardiogram

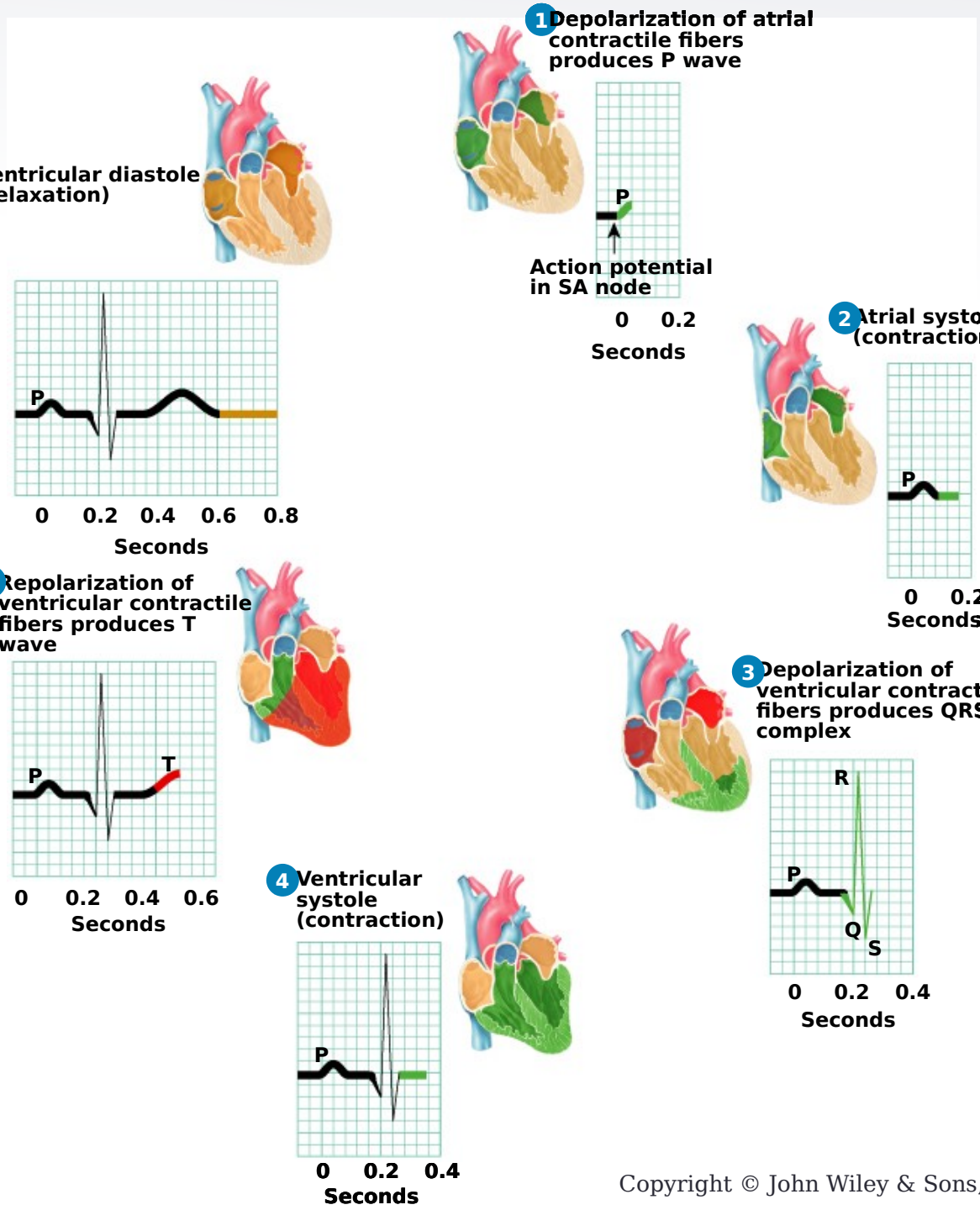
- An ECG recording can help us determine normal from abnormal cardiac activity:
  - Abnormal ECGs show problems within the conduction pathways, whether or not the heart is enlarged, or if certain regions are damaged.



The Electrocardiogram

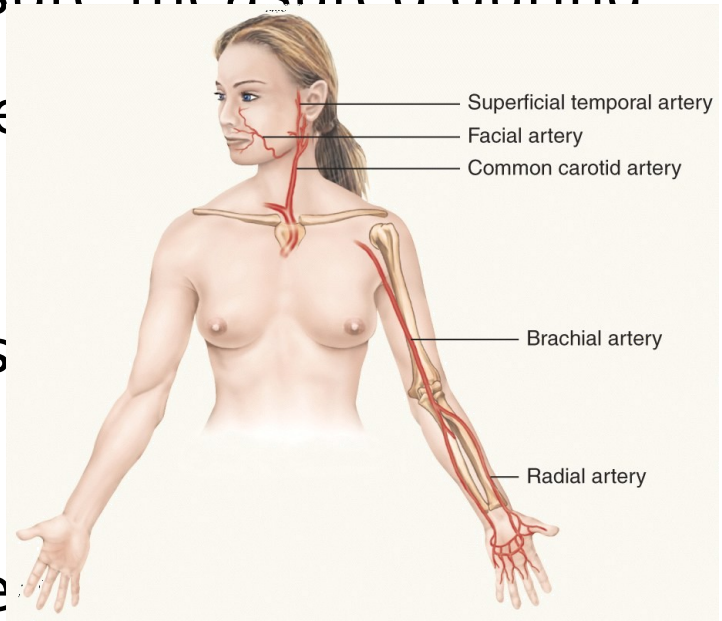
- The major deflections and intervals in a normal ECG include:
  - P wave - atrial depolarization
  - P-Q interval - time it takes for the atrial kick to fill the ventricles
  - QRS wave - ventricular depolarization and atrial repolarization
  - S-T segment - time it takes to empty the ventricles before they repolarize (the T wave)





Blood Pressure

- Blood Pressure is usually measured in the larger conducting arteries where the high and low pulsations of the heart can be detected – usually the brachial artery.
  - **Systolic BP** is the higher pressure measured during left ventricular systole when the aortic valve is open.
  - **Diastolic BP** is the lower pressure measured during left ventricular diastole when the valve is closed.

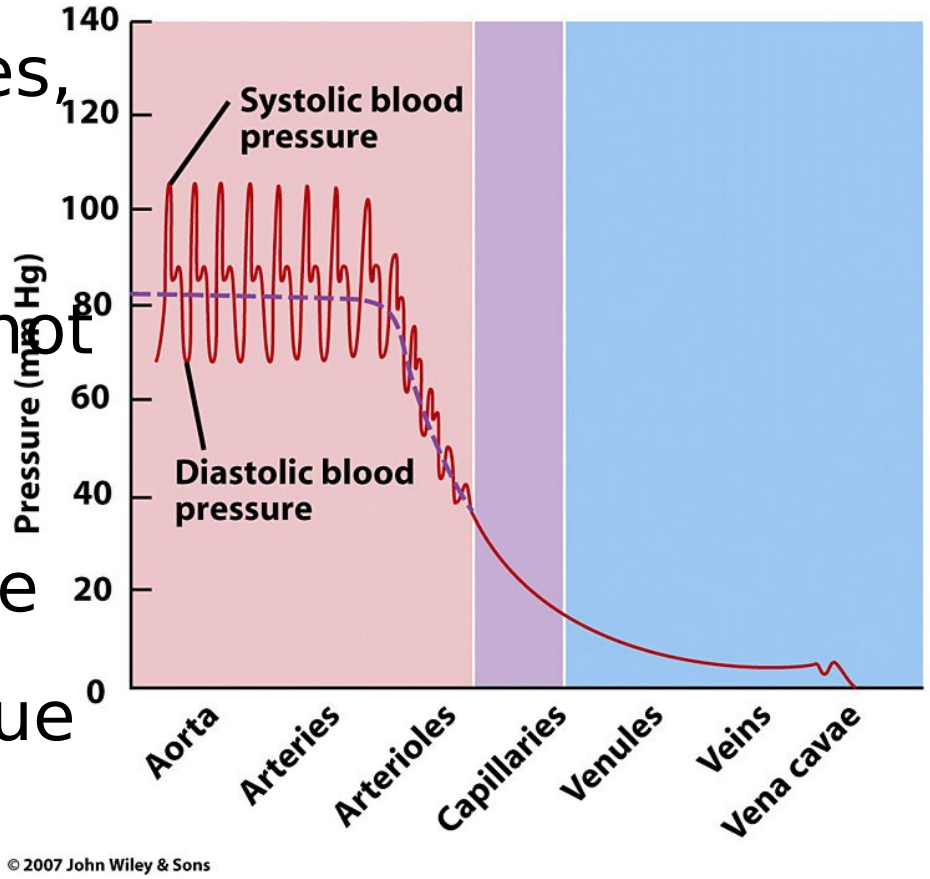


Blood Pressure

- **Normal BP** varies by age, but is approximately 120 mm Hg systolic over 80 mmHg diastolic in a healthy young adult (in females, the pressures are often 8–10 mm Hg less.)
  - People who are in good physical condition or who have a favorable genetic predisposition have lower BPs.
- It is often best to refer to the blood pressure as a single number, called the **mean arterial pressure (MAP)** .

Blood Pressure

- In a person with a BP of 120/80 mm Hg, MAP = 1/3 (120-80) + 80 = 93.3 mm Hg.
- In the smaller arterioles, capillaries, and veins, the BP pulsations are not detectable, and only a mean BP is measurable (see the purple and blue areas of this figure).



Cardiac Cycle

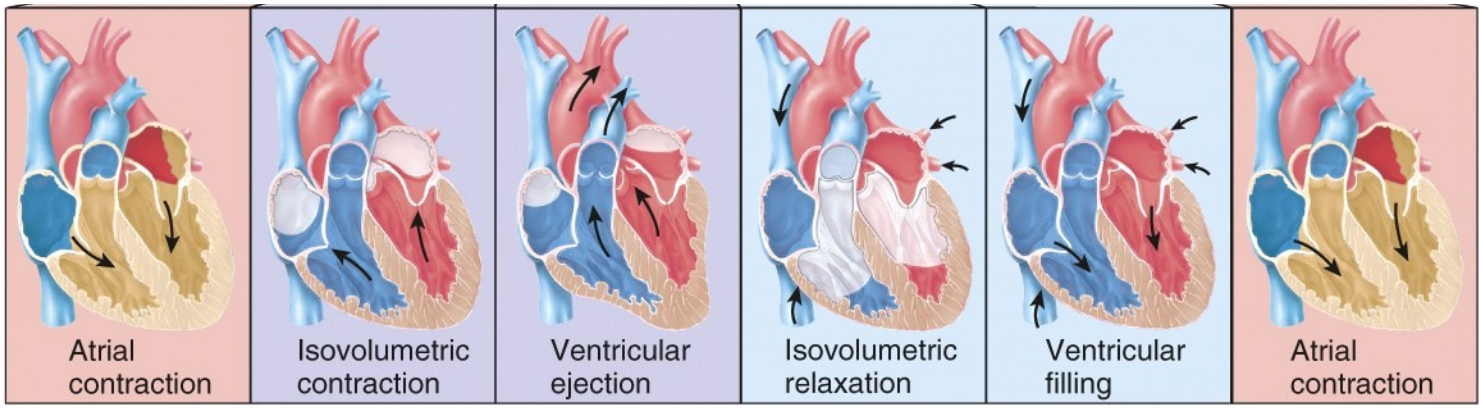
- The **cardiac cycle** includes all events associated with one heartbeat, including diastole (relaxation phase) and systole (contraction phase) of both the atria and the ventricles.
- In each cycle, atria and ventricles alternately contract and relax.
  - During atrial systole, the ventricles are relaxed.

Cardiac Cycle

- Since ventricular function matters most to the body, the two principal events of the cycle for us to understand are **ventricular filling (during ventricular diastole),** and **ventricular ejection (during ventricular systole)**.
  - The blood pressure that we measure in the arm is a reflection of the pressure developed by the left ventricle, before and after left ventricular systole.

Cardiac Cycle

- The sequence of events in one cardiac cycle is shown in Figure 20.14. Pay particular attention to the left ventricle:
  - 1st is atrial systole
  - Followed by atrial diastole and ventricular



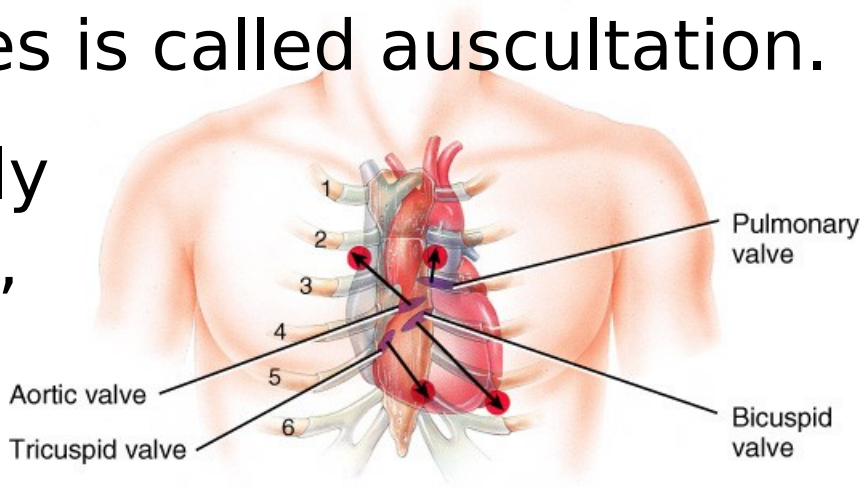
(e) Phases of the cardiac cycle

Cardiac Cycle

	Valves		
	AV	**SL Outflow**	
Ventricular diastole	Open	Closed	Atrial systole
Ventricular systole	Closed	Open	Early atrial diastole
Ventricular diastole	Open	Closed	Late atrial diastole

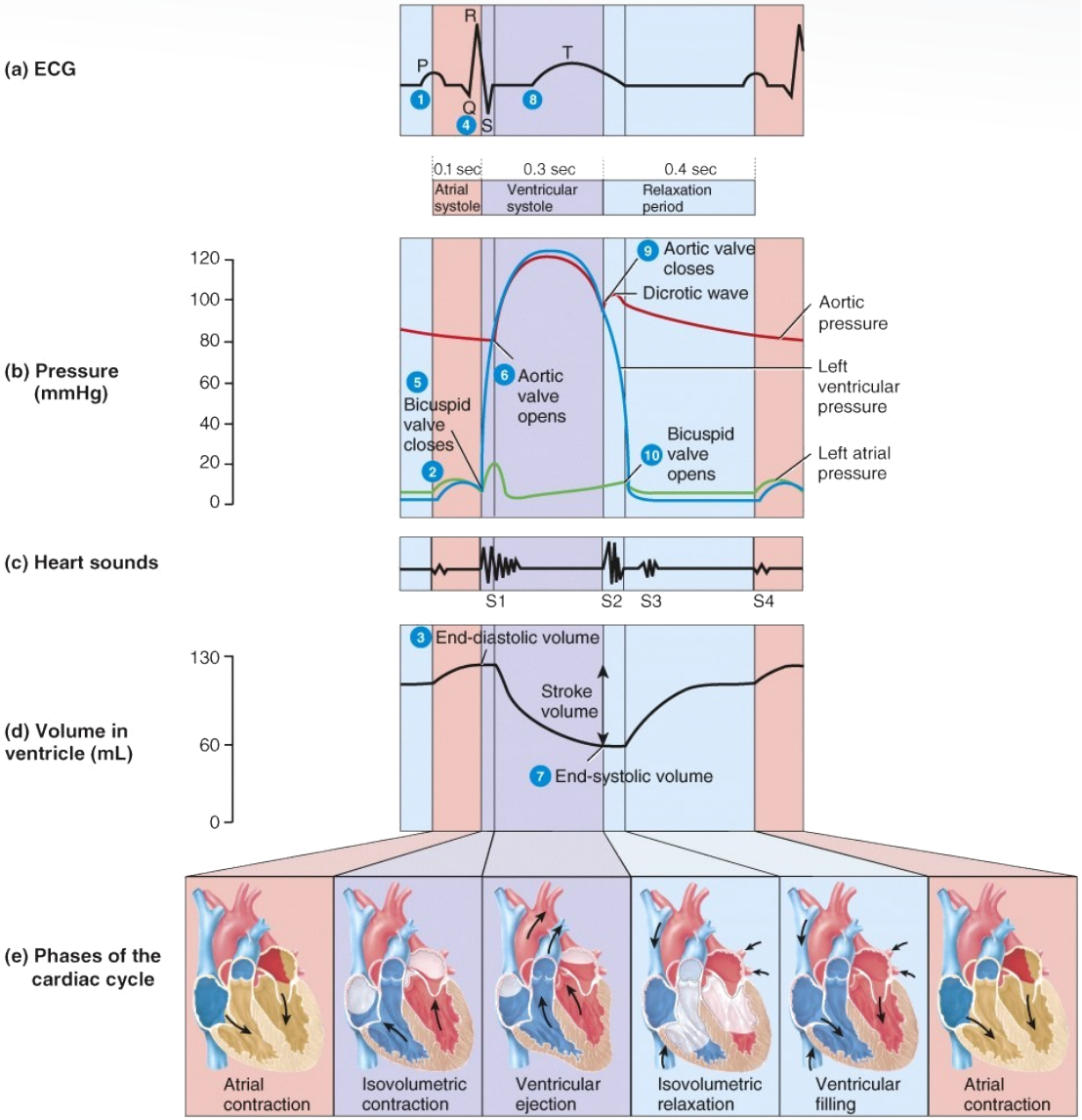
Cardiac Cycle

- During the cardiac cycle, all 4 of the heart valves have a chance to open and close. Listening (usually with a stethoscope) to the sounds the heart makes is called auscultation.
- Valve opening is usually silent. The “lubb dupp” we associate with heart auscultation is produced by valve closure (in pairs – see p. 740 left side)



(b) Anterior view of heart valve locations and auscultation sites

Cardiac Cycle



Cardiac Cycle

- The average time required to complete the cardiac cycle is usually less than one second (about 0.8 seconds at a heart rate of 75 beats/minute).
  - 0.1 seconds – atria contract (atrial “kick”), ventricles are relaxed
  - 0.3 seconds – atria relax, ventricles contract
  - 0.4 seconds – relaxation period for all chambers, allowing passive filling. When heart rate increases, it’s this relaxation period

Cardiac Output

- The stroke volume (SV) is the volume of blood ejected from the left (or right) ventricle every beat. The cardiac output (CO) is the SV x heart rate (HR).
  - In a resting male, CO = 70mL/beat x 75 beats/min = 5.25L/min.
- On average, a person's entire blood volume flows through the pulmonary and systemic circuits each minute.

Cardiac Output

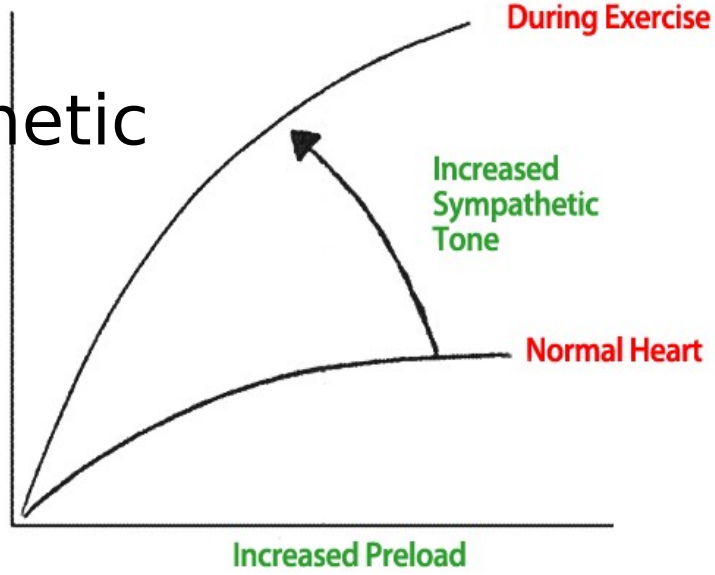
- The **cardiac reserve** is the difference between the CO at rest and the maximum CO the heart can generate.
  - Average cardiac reserve is 4-5 times resting value.
    - Exercise draws upon the cardiac reserve to meet the body's increased physiological demands and maintain homeostasis.

Cardiac Output

- The cardiac output is affected by changes in SV, heart rate, or both.
- There are 3 important factors that affect SV (p. 741):
  - The amount of ventricular filling before contraction (called the preload)
  - The contractility of the ventricle
  - The resistance in the blood vessels (aorta) or valves (aortic valve, when damaged) the heart is pumping into (called the afterload)

Cardiac Output

- The more the heart muscle is stretched (filled) before contraction **(preload),** the more forcefully the heart will contract. This phenomenon is known as **Starling's Law of the heart**.
  - Stimulation of the sympathetic nervous system during exercise increases venous return, stretches the heart muscle, and increases CO



Cardiac Output